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SCALE MODEL NONDESTRUCTIVE EXAMINATION (NDE) ROUND ROBIN TEST

The Evaluation of NDE Techniques for Determining Offshore Structural Integrity

FREQUENCY RESPONSE METHOD

Prepared by

Energy and Resources Division
Development Planning Directorate
The Aerospace Corporation
El Segundo, California 90245

Principal Investigators: Drs. Sheldon Rubin and Robert Coppolino
Project Engineer: J. Arthur Conley

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Technical Officer: J. Gregory USGS

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Reston, Virginia 22092

Foreword

The Aerospace Corporation initiated efforts under an Interagency Agreement between the U.S. Geological Survey and the U.S. Air Force (Space Division) in February 1980 to formulate, analyze and deliver a frequency response monitoring evaluation of the results of a structural integrity test program (NDE Round Robin) conducted on a subscale model of a four-leg fixed offshore platform.

This report has been prepared for the Conservation Division, U.S. Geological Survey under Interagency Agreements Nos. 0-6104-05813(64) and 0-6104-05813(60). The Technical Officer for these Interagency Agreements is Mr. John Gregory, Research Program Manager, Branch of Marine Oil and Gas Operations.

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Acknowledgements

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1. INTRODUCTION

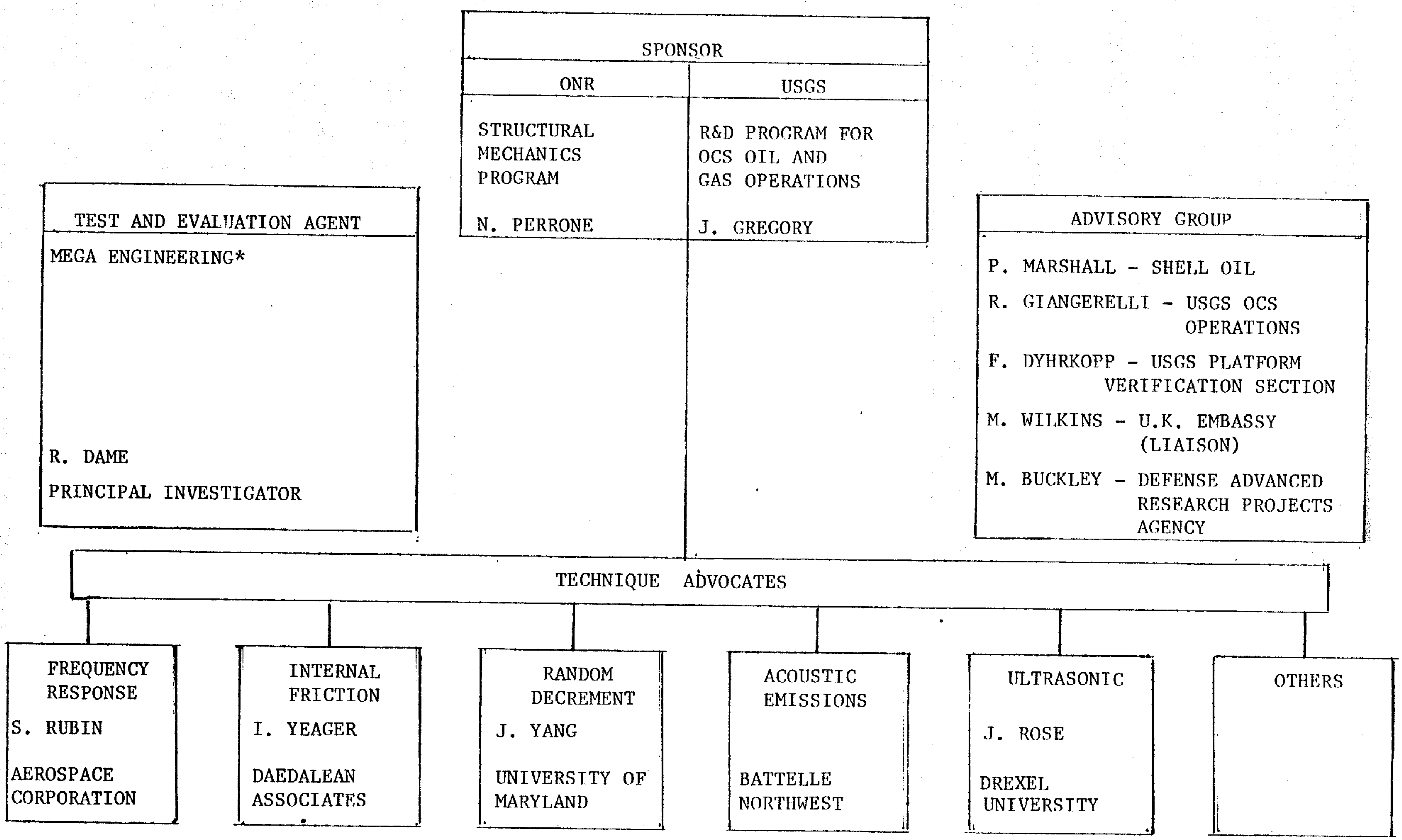
The quest for the discovery of new oil and gas deposits has motivated government and industry to expanded exploration of the Outer Continental Shelf (OCS) for new sources of supply. The hostile environments encountered in these explorations have stimulated considerable effort in the formulation of new methods for verification of the structural integrity of fixed offshore platforms. Progressively larger structures, deeper waters and more severe weather conditions have prompted a growing concern for the safety of diving personnel required for underwater inspections, platform crews, and the environment.

Historically, the structural integrity of fixed offshore platforms has been periodically assessed by the use of divers or remotely controlled unmanned submersibles. These methods have also been used to perform inspections after storms, collisions, or other occurrences which could damage the platform. Even in fairly shallow waters, these techniques are only marginally effective, time consuming and costly. These problems are magnified in deeper OCS areas where saturation diving is required. As a consequence, platform monitoring techniques are desired which reduce inspection time and costs and provide a reliable structural integrity indicator in lieu of detailed visual inspections. The U.S. Geological Survey (USGS) considers such platform monitoring techniques as potentially useful in their OCS Platform Verification Programs. These techniques can also be used by industry during the life of the platform to ensure personnel and environmental safety.

In reponse to this need, the USGS initiated a study in October 1976 with The Aerospace Corporation under Contract 14-08-0001-15989 to (a) review existing inspection approaches in the United States and the North Sea; (b) perform analyses of selected options; and (c) develop alternative instrumentation configurations for possible operational applications. It was determined that the monitoring of the modes of structural vibration was being applied commercially in the North Sea and appeared to provide the most promising approach. It was, however, not possible to fully evaluate the applications in use because of proprietary restrictions. That fact led to tests performed by Aerospace on the Shell Oil Company Platform C on South Pass OCS Tract 62 in the Gulf of Mexico as a means of addressing matters of instrumentation, data analysis, interference from operating machinery, modal identification and the effects of a high degree of structural redundancy. The Shell platform is located in 327 ft (100 m) of water, and until a few years ago, was among the taller structures in the Gulf. A total of 26 hours of ambient vibration data were recorded, which included periods of both calm and stormy sea conditions. Only a quick-look analysis was conducted on this data. This study was completed in October 1977 and is covered in Aerospace Report No. ATR-77(7627-02)-1, "Instrumentation of Fixed OCS Platforms".

An ensuing contract (14-08-0001-17224) was initiated by the USGS with The Aerospace Corporation in September 1978 to: (a) perform a detailed analysis of the vibration data recorded during the previous contract to extract modal frequencies and shape parameters; (b) develop a dynamic model of the subject offshore platform which yields modes in good agreement with those measured; (c) determine modal changes associated with single structural failures using the dynamic model; and (d) develop a plan for evaluating prototype instrumentation. This study was completed in June, 1979 and the results are documented in Aerospace Report No. ATR-79(7787)-1, "OCS Instrumentation Monitoring Evaluation."

As a result of the Aerospace studies and studies by others of NDE techniques (i.e. Internal Friction Monitoring, Random Decrement, Acoustic Emissions, Ultrasonic, and more), the U.S. Geological Survey proposed to assess the applicability of the various techniques in a laboratory test program. The "NDE Round Robin" program was formulated to focus, evaluate, and document the NDE activities of the varied technique advocates, as well as to compare these methodologies and others which appear applicable to underwater inspection and monitoring. The "NDE Round Robin" program, which consists of baseline and "blind" testing of subscale models, is sponsored jointly by the Office of Naval Research and the U.S. Geological Survey. The organization of the participants in the "NDE Round Robin" program is shown in Figure 1.1.



*IDENTIFIED FOR TECHNIQUES 1, 2 AND 3.

Figure 1.1 NDE Round Robin Organization

The Aerospace Corporation was chosen as the advocate for the Frequency Response Monitoring Technique and placed under contract to analyze test data from the "NDE Round Robin" program. The products of this analysis are contained herein.

1.1 Summary

This report presents the results of the application of the frequency response monitoring technique to vibration data obtained in the structural integrity test program (NDE Round Robin). Vibration tests were conducted on a simplified subscale model of a 4-leg offshore platform, with its base fixed and not submerged in water.

In the process of evaluation of the data, a new and promising approach evolved. This approach monitors the changes in the flexibility of the structure and its foundation using the shapes of the fundamental modes, including underwater leg positions. This approach holds considerable promise and is recommended for further investigation.

Three variations of frequency response monitoring were utilized to assess the blind damage scenarios. All were found to have utility in the identification and localization of the damage condition. A high degree of success was achieved.

Damage Scenario		Aerospace Assessment*
#1	A1 Leg - Foundation Released	Correct - 100% confidence
#2	Lowest horizontal brace half cut thru at both ends (level 5)	Correct - 50% confidence
#3	Removal of lowest K brace (level 4-5)	Correct - 100% confidence
#4	No failure	Correct - 100% confidence

*Appendix B

1.2 Goals and Objectives

The goal of the "NDE Round Robin" program is to evaluate techniques that might merit further development for the examination of offshore structures to determine their structural integrity. The established program plan is included in Appendix A.

The primary goal of this study is to utilize frequency response based technique to identify, in a "blind" mode, the presence of induced failure on the model structure.

Secondary goals include: (a) the discrimination between failure and non-failure conditions, (b) the discrimination of the degree of damage, and (c) the determination of the location of the damage.

1.3 Scope

A simplified subscale model of a four-leg platform configuration (Figure 1.2) was shaker excited in air to produce data for frequency response analyses. Both global structural evaluation and evaluation of brace member groups were considered. The intent is to evaluate the model in a way which is meaningful to actual offshore platforms. Possible nonfailure changes, for example, include simulated marine growth and a change in deck mass. Failure type changes include severed members, joint cracking, and foundation impairment. Upon completion of the evaluation of this study, it is planned to decide whether or not to conduct a similar study on a model of an eight-leg platform (Figure 1.3) involving more realistic structural details and foundation conditions.

Mega Engineering, the Test and Evaluation Agent, was responsible for test execution. The test laboratory was at the NASA Goddard Space Flight Center, Greenbelt, Maryland. The baseline tests were open to advocate participation; however, since the purpose of the evaluation was to assess the utility of each concept for failure identification, the advocates were "blind" to a series of "damage scenario" tests (i.e. they had no knowledge of failure or nonfailure changes in the models).

The test procedures (calibration, sensor and shaker positioning, data formats, etc.) were developed by each of the technique advocates to address the following possible scenarios (from section 3.5 of Appendix A):

1. Major Damage
   - a) Severed diagonal brace on one face at midlevel,
   - b) Two severed diagonals at midlevel, one on each of opposite faces,
   - c) Severed horizontal at base,
   - d) Two severed horizontals at base, one on each of opposite faces,
   - e) Changed foundation condition.

2. Minor Damage
   - a) Bent diagonal members in upper bay,
   - b) Change in deck mass,
   - c) Simulated marine growth,

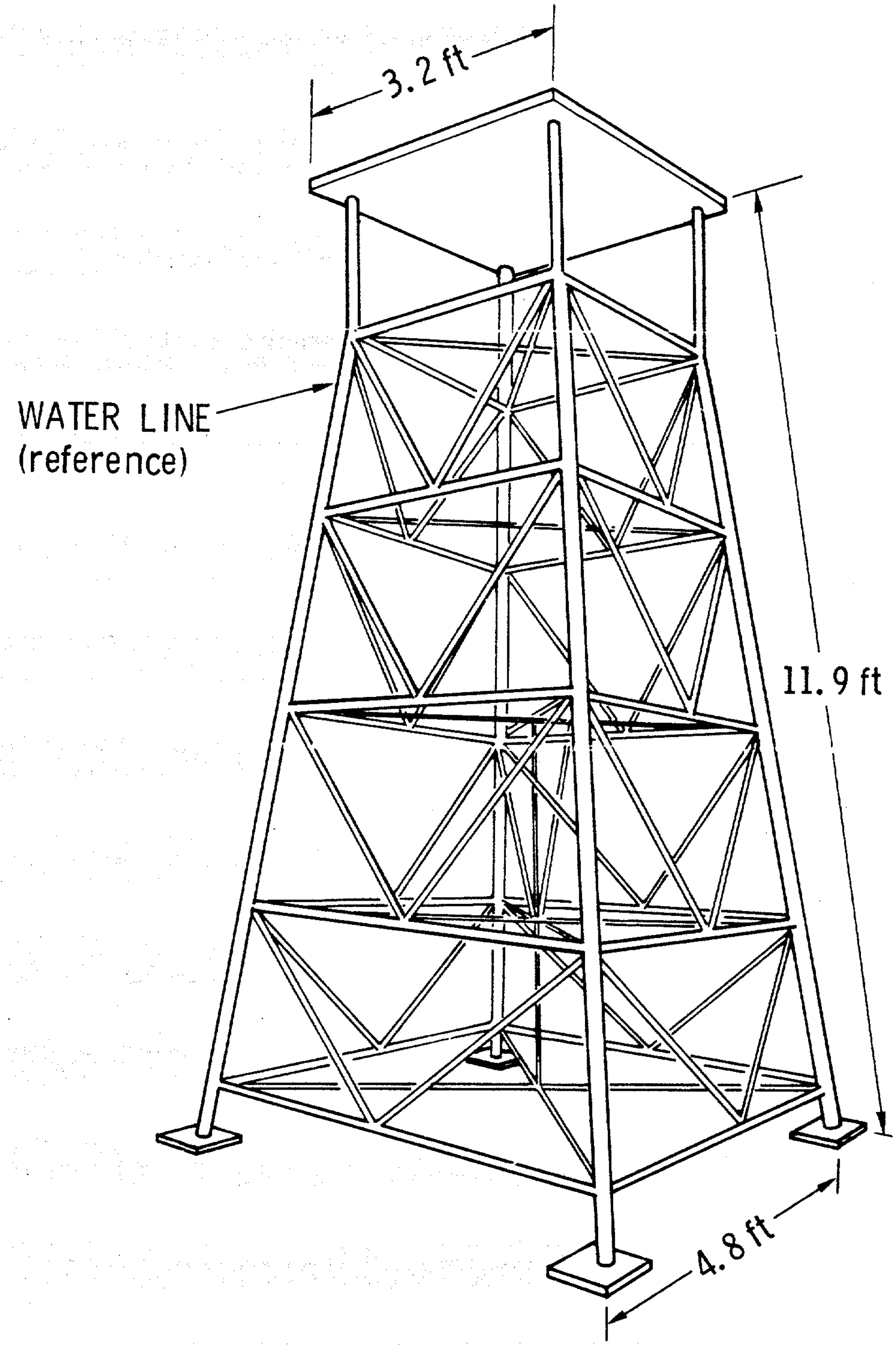
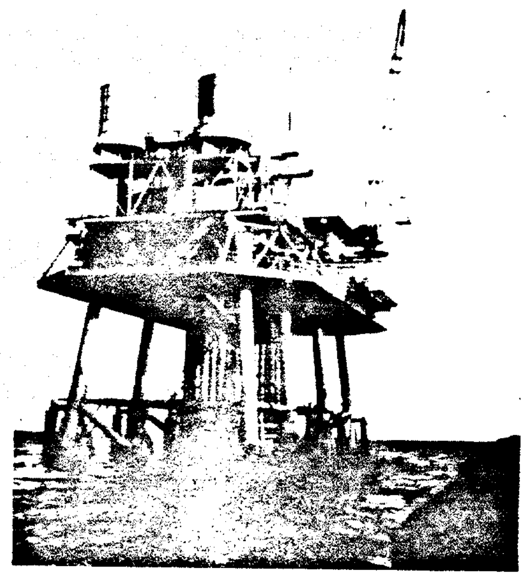


FIGURE 1.2 FOUR-LEG PLATFORM

Designed by and drawings provided by Gulf Oil Co. Scaled and built by the University of Maryland Physics Department Shop.



VIEW OF SP-62C

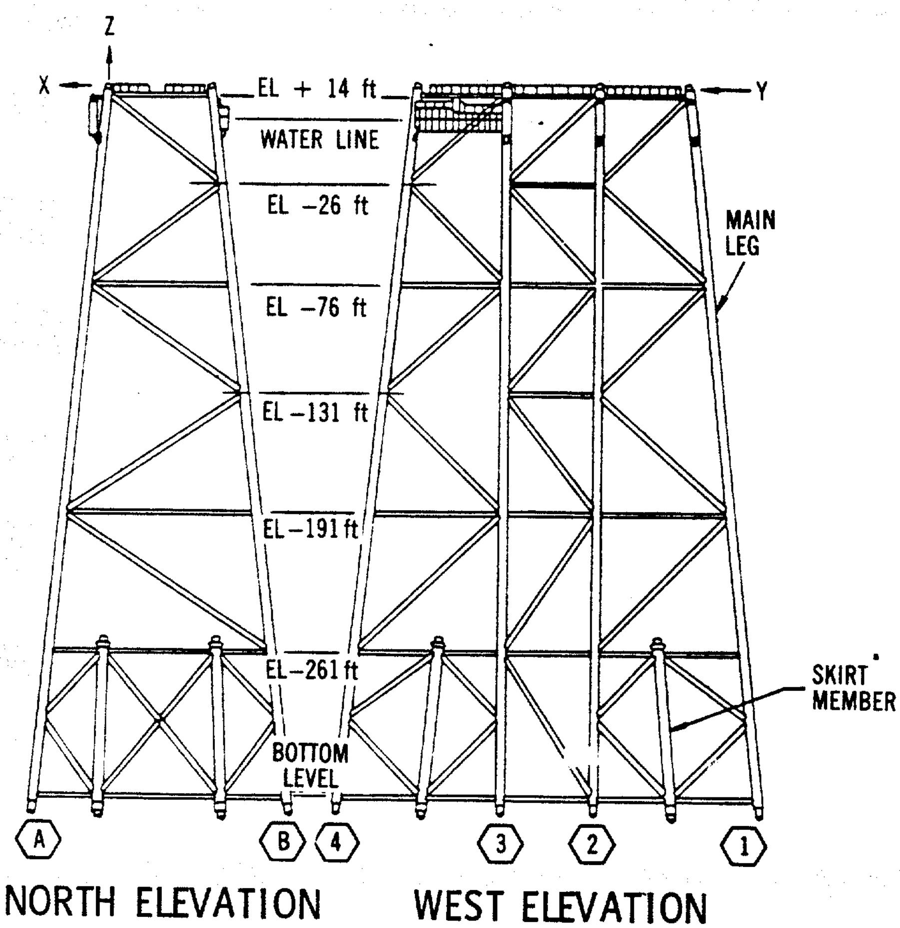


FIGURE 1.3 BASE SECTION OF SP-62C
(Courtesy of Shell Oil Company)

d) Crack in one or two horizontal members,

e) Progressive cracking of horizontal and diagonal members,

f) Installation of one or two riser pipes.

1.4 Ground Rules

The program was conducted under the following ground rules:

1. The "NDE Round Robin" test program will be performed at the NASA Goddard Test Facility by Mega Engineering, the Test and Evaluation (T&E) agent, in accordance with procedures supplied by the advocates of the various techniques.

2. There will be no on-site interaction with the test program or with the test structure by the advocates or their representatives (following the baseline testing).

3. The number of data channels will not exceed 35 per advocate.

4. The number of changes in shaker location or direction will not exceed three.

5. The test setup will be fixed by each advocate in advance of the blind tests.

6. Test data will be simultaneously sent to all advocates in the form requested by the advocates.

7. Forms for reporting the evaluation results will be supplied to each advocate for reporting findings and rationale. As a goal, completion and transmittal to the T&E Agent will not exceed two months after receipt by each advocate.

8. The T&E Agent will evaluate the advocate assessments and will develop a matrix to illustrate comparative results.

9. After the analyses have been subjected to a comparative evaluation, a meeting of all participants will be held to discuss the evaluation results.

10. A final technical report will be submitted to document the analysis technique, rationale, results and recommendations.

1.5 Approach

In general terms the frequency response monitoring concept relies on the identification of natural frequencies and associated mode shape parameters of a platform. Changes in the modal parameters serve as indicators of the presence of underwater structural failure and its location. Diagnosis requires the availability of modal sensitivity results from analysis of a mathematical dynamic model of the platform. Discrimination of failure versus nonfailure causes of modal change is a necessary factor in the success of the method.

To apply this concept in the Round Robin program, tests were conducted on the model to identify its vibration modes in a baseline (undamaged) configuration. Also, a mathematical dynamic model was implemented on a computer and used to conduct modal sensitivity studies for use in the evaluation of the damage scenarios.

The approach taken in the testing is to measure frequency response functions for acceleration per unit force with the required resolution over the frequency range of interest. The modal frequencies and shapes are then extracted for use in assessing damage or other change. The excitation employed is shaped broad band random. Digital data acquisition and averaged Fast Fourier Transform (FFT) processing are employed to develop the complex frequency response functions and associated coherence functions. Two shaker locations are employed to provide duplicate information for checking of data consistency, to forestall the possibility of failure to excite any significant modes, and for use, if necessary, to separate very closely spaced modes.

The findings from the blind test data are identified within the following approaches (pertaining to the complexity of acquiring the needed data in a field situation):

1. Fundamental Modes, Abovewater Positions

   This approach involves data that could be obtained accurately from ambient excitation and with abovewater located accelerometers (Reference 1). This is basically the application of classical global mode monitoring to this model. In field use, modes from the second and third global groups, when identifiable, would also be employed for diagnosis of failures. Such modes, however, were not included for the model since they occurred at an unrealistically high frequency (compared to actual platforms) relative to the fundamentals and lower brace modes.

2. Fundamental Modes, Abovewater and Underwater Leg Positions

This is an extension to approach 1 involving accelerometers on the legs at the various underwater levels in addition to abovewater locations. This underwater placement is made possible in the field without use of divers if the platform is equipped with instrument chutes. Such a chute is typically a square tube, welded to the side of a leg, that enables entry of an instrument package from abovewater and clamping of that package at any water depth (limited only by the extent of the chute). Such chutes have been included during construction on several existing and upcoming platforms in the Gulf of Mexico and off the Southern California Coast. This approach facilitates the application of our new concept, "flexibility monitoring", to be discussed shortly. It improves the sensitivity and localizing capability for failure detection. Ambient data is believed to be adequate for field aplication.

3. Brace Modes, Abovewater Positions

This category involves abovewater shaking and abovewater responses to detect certain brace modes. Such modes would typically not be identifiable in the field from ambient abovewater data because of the interference of platform machinery induced vibration and because of the relative weakness of the modal responses at abovewater locations.

It was decided not to utilize accelerometers mounted on the underwater braces for "local member" evaluations. Although a limited number of brace accelerometers were part of the baseline testing, and these remained for the subsequent tests, those accelerometers were not employed for the damage evaluations. Many more such accelerometers would have been needed to monitor all of the K-braces on the model. An alternative would have been to move groups of accelerometers to selected individual K-brace sections based upon other observations. It was determined that the limitation on the number of accelerometers, the requirement to fix the test setup in advance, and the prohibition against test interaction ruled out application of "local member" monitoring in this program.

Returning to approach 2, the "flexibility monitoring" concept emerged in our planning for evaluation of possible techniques in this program. The concept takes advantage of the basic shear beam behavior of a fixed offshore structure, as well as the fact that the three fundamental mode shapes closely approximate deflections due to corresponding static loading at the decks. The goal is to approximate the direct measurement of shear flexibility across individual bays of the jacket, as well as gross flexibilities of the foundation. The term "flexibility" is used to imply deflection per unit force. The forces applied to the top of the jacket can be inferred to be proportional to the measured relative deflections of the above-water structure between the deck and jacket top (boat level). An estimate of gross shear flexibility of a bay is then proportional to the corresponding relative deflection across the bay, divided by the abovewater relative deflection. Similarly, by appropriate relative deflection measurements at the foundation, normalized by the same abovewater force measure, various foundation flexibilities are estimated.

The attractive characteristics of such an approach for field application are:

1. Total reliance is placed upon detection of the fundamental modes, thus completely avoiding identification and accuracy difficulties of higher modes.

2. There is relatively low sensitivity to deck mass changes, to marine growth, to brace flooding, or to conductor/guide contact uncertainty.

3. Sensitivity to damage and the ability to localize damage is enhanced relative to the usual global mode monitoring because flexibility changes

are detected on a per structural bay basis and separately for the base/foundation portion. Thus, sensitivity is not reduced for tall structures having numerous bays, or those having a soft foundation, as is the case for global mode monitoring. For example, the model structure in the Round Robin program was analyzed to determine indicated flexibility changes for a series of damage and nondamage possibilities. The results for a series of four diagonal severance cases, in the affected first lateral mode, is shown in Figure 1.4. The percent frequency reduction in the mode for each failure case is shown by the Δ f/f values. Note that the flexibility increases for the damaged bays vary from about 80 to 180 percent, while much smaller changes (from a 20-percent reduction to a 4-percent increase) are indicated for the nondamaged bays due to minor deviations from the idealized behavior assumed. The face on which the damage exists is indicated clearly by the much larger deflection across that face relative to the opposite undamaged face. Computed results for major deck mass and marine growth changes show negligible influence on the flexibility indications.

Two complications of the new concept are the needs for accuracy in the underwater placement of sensors and for the relative amplitude measurements. Underwater placement, as an operational issue, is mitigated by the fact that only positions on main legs are required. In fact instrument chutes, which have been placed on corner legs of several platforms installed in the last few years for design evaluation purposes, are ideally suited to the needs of flexibility monitoring. As regards amplitude accuracy, this is believed to be the key measurement issue for flexibility monitoring.

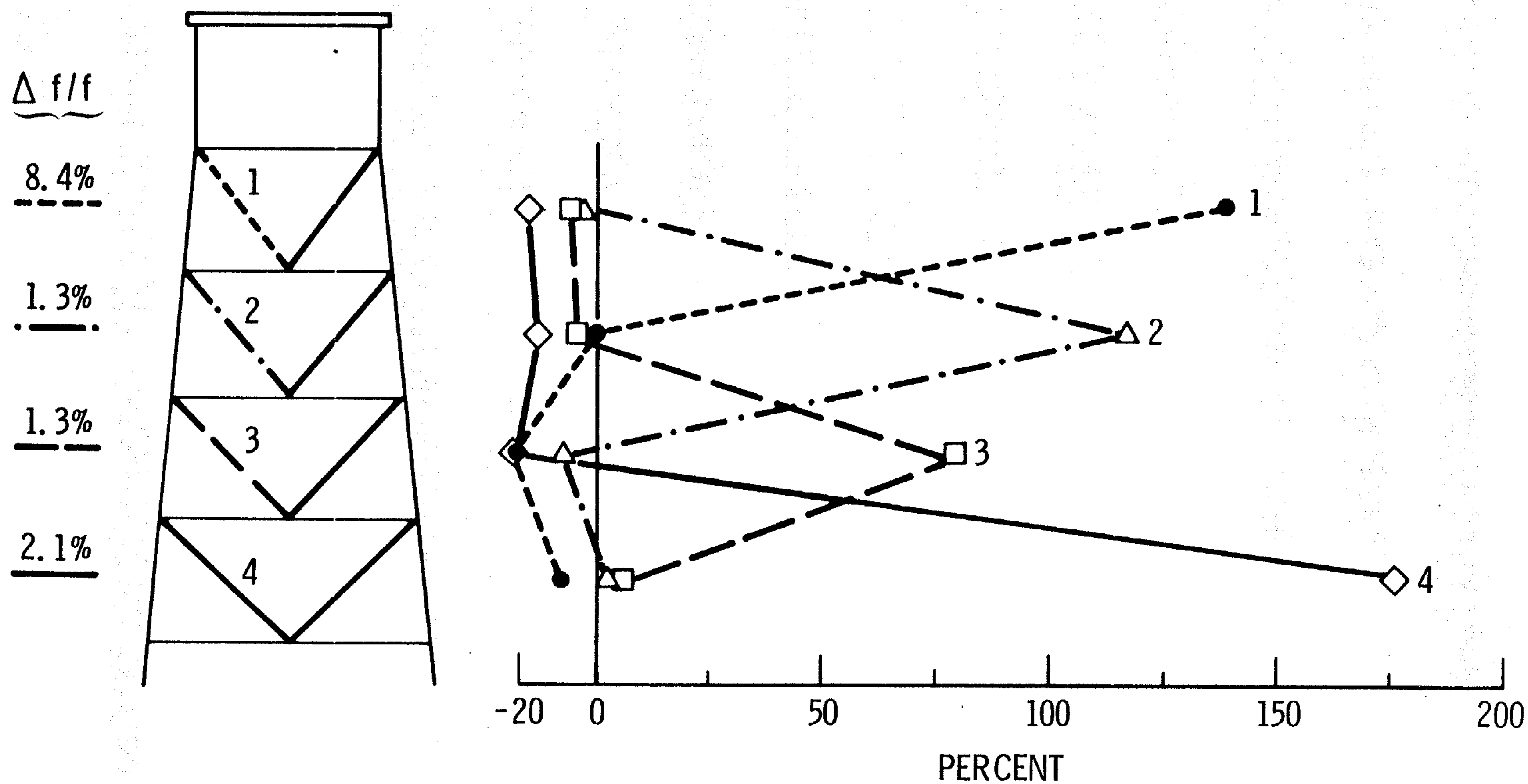


FIGURE 1.4 INDICATED FLEXIBILITY CONSEQUENCES IN THE FUNDAMENTAL LATERAL MODE FOR DIAGONAL FAILURES

2.0 Test Configurations

2.1 Model Structure

The four-leg platform model is scaled approximately 1:13.8 from the actual dimensions of Platform B, Block 48, South Marsh Island, Gulf Oil Corporation which was erected in 1965 in 105 feet of water. No piles are included and the leg bottoms are rigidly bolted to a seismic floor block in the test lab. The model stands 11.9' high and is 4.8' square at the base and 3.2' square at the top (See Figure 1.2). The legs are 2-inch(O.D.) steel pipe with a 0.109-inch wall and all the brace members are 3/4-inch(O.D.) steel pipe with a 0.065-inch wall. The model is all welded, except for a 1.5-inch thick stiffening aluminum honeycomb plate bonded onto a 0.112-inch thick steel top plate. This stiffening was done at our request to prevent an unrealisticaly low fundamental plate mode of the deck of the model. In an actual platform the upper portion consists of a truss stiffened super-structure deck. Our goal was to achieve a first plate frequency of the model deck above 60 Hz. The measured frequency was 90 Hz.

In the future, tests can be conducted with (a) a simulated soil foundation, (b) a more representative model such as the eight-leg model depicted in Figure 1.3, including pile and conductor members, and (c) immersion of the model in water.

2.2 Instrumentation and Forcing

The four-leg platform is instrumented with a total of 69 accelerometers (for the three advocates who employ the platform test configuration, Frequency Response - Aerospace, Random Decrement - University of Maryland, and Internal Friction - Daedalean Associates), mostly mounted on 3/4-inch aluminum cubes which are bonded to the structure. The sensors are center bolted to the cubes. Our 34 accelerometers (Endevco 2221D) are located as shown schematically in Figure 2.1.

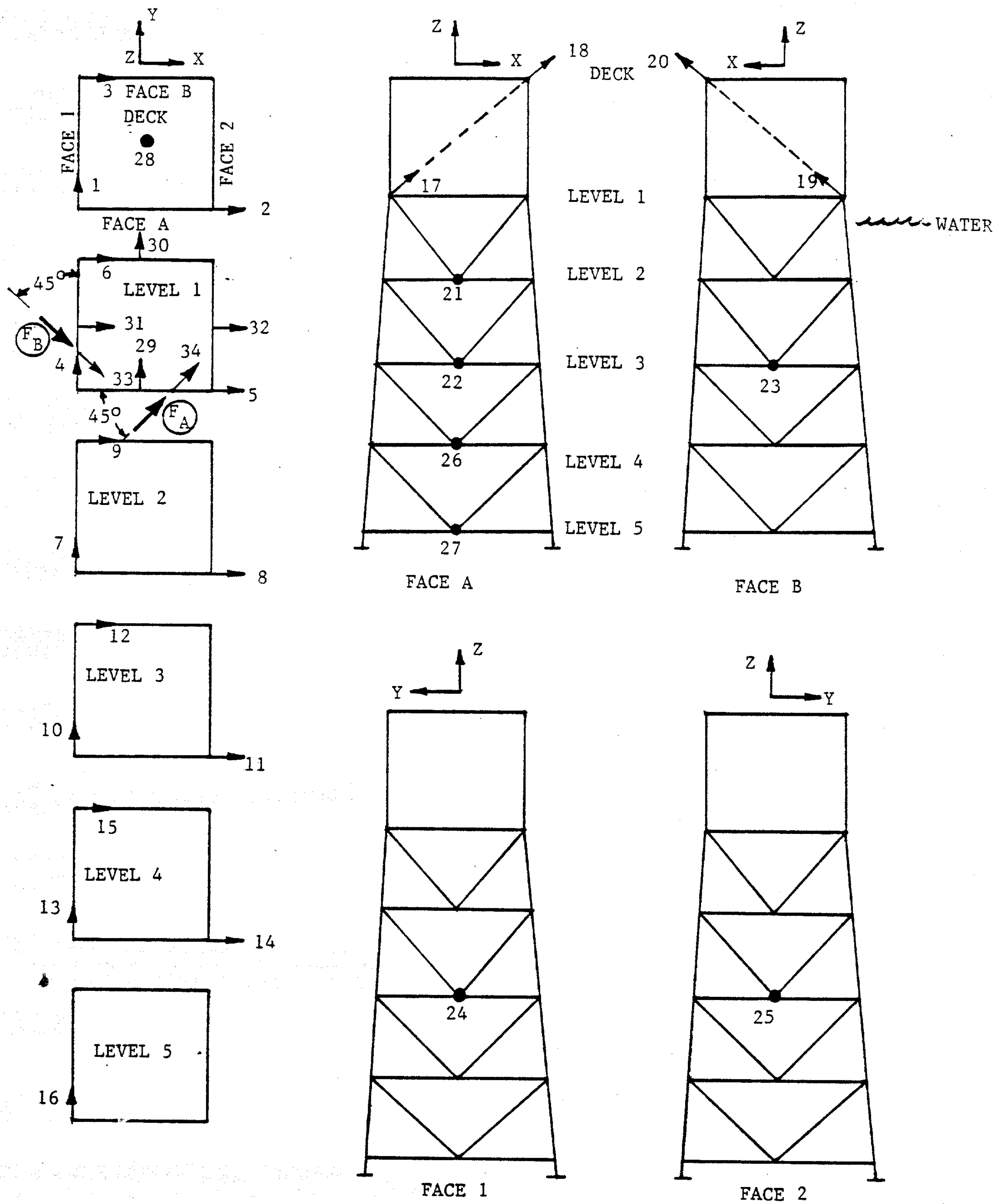


FIGURE 2.1

ACCELEROMETER & FORCE POSITIONS-AEROSPACE TESTS

For approach 1 (fundamental modes, abovewater positions), accelerometers 1-6 are employed. (The deck and level 1 are abovewater for an actual structure.) For approach 2 (fundamental mode, abovewater and underwater positions), accelerometers 1-15 and 17-20 are employed. For approach 3 (brace modes, abovewater positions), accelerometers 1-6 and 29-32 are employed. Broadband random forcing was generated using a 10-pound shaker at two different positions on the horizontals of level 1 as seen on Figure 2.1 (namely F_A and F_B).

3.0 Baseline Testing

The objective of the baseline testing is to prepare for the application of frequency response monitoring to the damage scenarios. In particular, the purposes are (1) to finalize the test configuration and data processing and 2) to identify the vibration modes of interest for the several application approaches identified in Section 1.5.

3.1 Test Setup

Prior modal analyses using a mathematical dynamic model (to be described in Section 4.0) had led to the desire to identify the three fundamental modes and the family of modes involving fundamental breathing (out-of-plane) modes of the K-brace sections. On this basis the accelerometer locations, the forcing positions, and the frequency range and resolution were determined.

A schematic of the setup is presented in Figure 2.1. The maximum number of accelerometers permitted by a test constraint, namely 34, are arranged as follows:

1-16: measure the three degrees of freedom (dof) for rigid-body horizontal motion of the deck and levels 1 to 4, and a single motion at level 5.

17-20: measure diagonally oriented motions at the deck and level 1 on faces A and B.

21-27: measure a selection of normal motions at K-brace nodes.

28: measures deck normal motion at its center.

29-32: measure out-of-plane level 1 motions at the centers of the four horizontal members.

33-34: measure motion along the line of action of the two forcing locations, F_A and F_B on two level 1 horizontal members.

Also, based upon the modal analyses, the forcing positions F_A and F_B were identified. These positions were chosen to permit excitation of the out-of-plane K-brace modes from abovewater positions and, at the same time, excite the three fundamental modes.

3.2 Data Acquisition and Processing

Six channels of data acquisition were available using a Time Data digital signal analyses system (Model TDA-53L). Each data run involved processing the applied force and five acceleration signals. Seven data runs were required to cover the 34 accelerometers for F_A forcing and another set of seven for the F_B forcing. Each group of six channels was anti-alias filtered, digitized at a 409.6 per second rate, and stored on a magnetic hard disc, then played back for FFT processing. Autospectra, frequency response functions, and coherence functions were obtained. The frequency range was 0 to 102.3 Hz with 0.1 Hz frequency line spacing. Seventy averages, overlapped 50%, and a Hann window were employed. All results were transferred to magnetic tape for later processing at Aerospace. Also, the frequency response functions were put onto a disc in a format compatible with a commercially available modal analysis system of The Structural Dynamics Research Corporation (SDRC).

In order to obtain acceptably high coherence at the lower leg positions for the fundamental modes, the excitation random force was shaped to accentuate the lower frequencies. An autospectrum of the resulting applied force is shown in Figure 3.1. Selected frequency response magnitude (FRF) and coherence functions are shown in Figures 3.2 - 3.4 (for accelerometers 2, 13, 22, respectively, and F_B forcing). Except at maxima and minima of the frequency responses, the coherence is seen to be high over the frequency range of interest of 15 to 70 Hz. The sharp drops in coherence at the modes (maxima) are related to the low resolution of the analysis (0.1 Hz) relative to the resonant bandwidths. The combination of the desire to cover such a wide frequency range and the extremely light damping of the model led to the poor resolution.

3.3 Calibrations

End-to-end relative calibrations of selected accelerometers were attempted for the frequency range of the fundamental modes (18 to 35 Hz). The method employed was

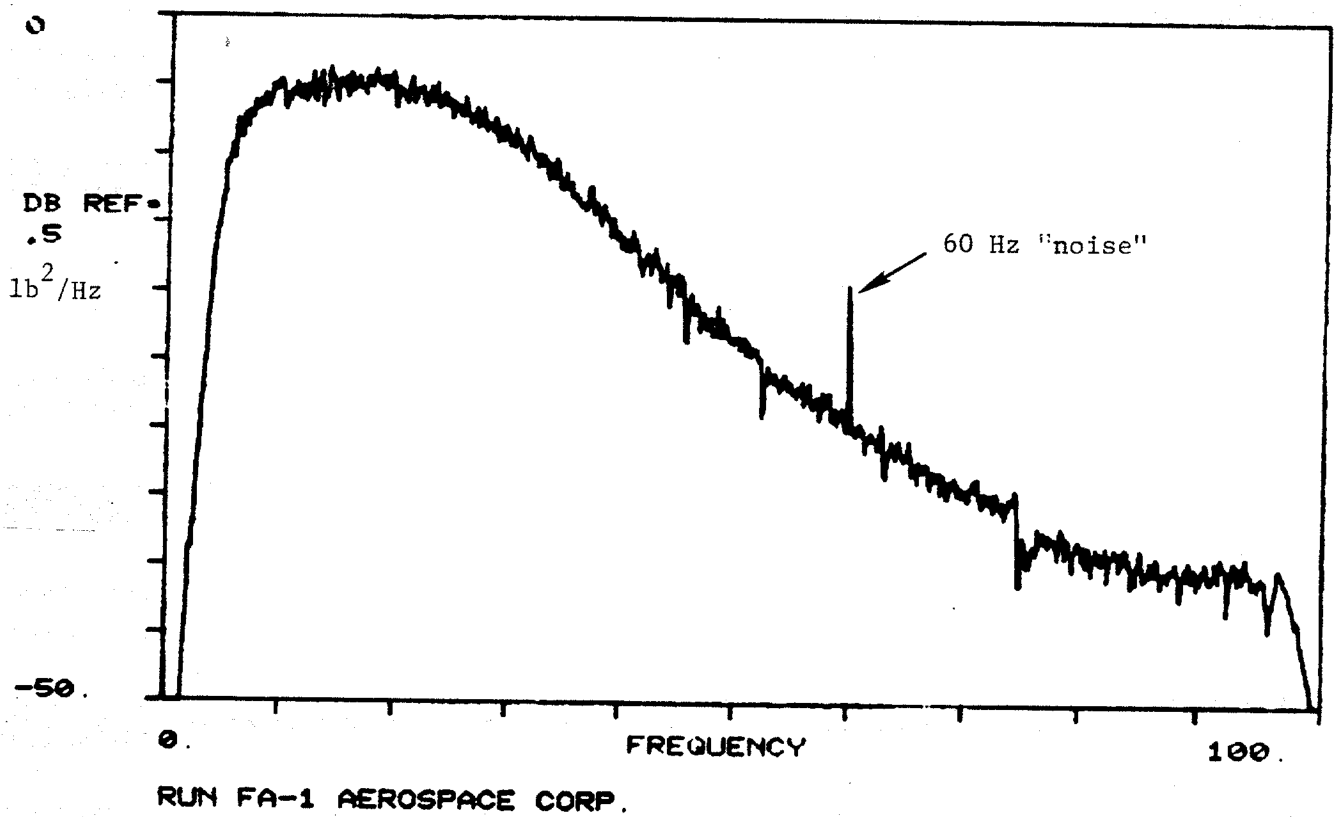


Figure 3.1 Autospectrum of Force.

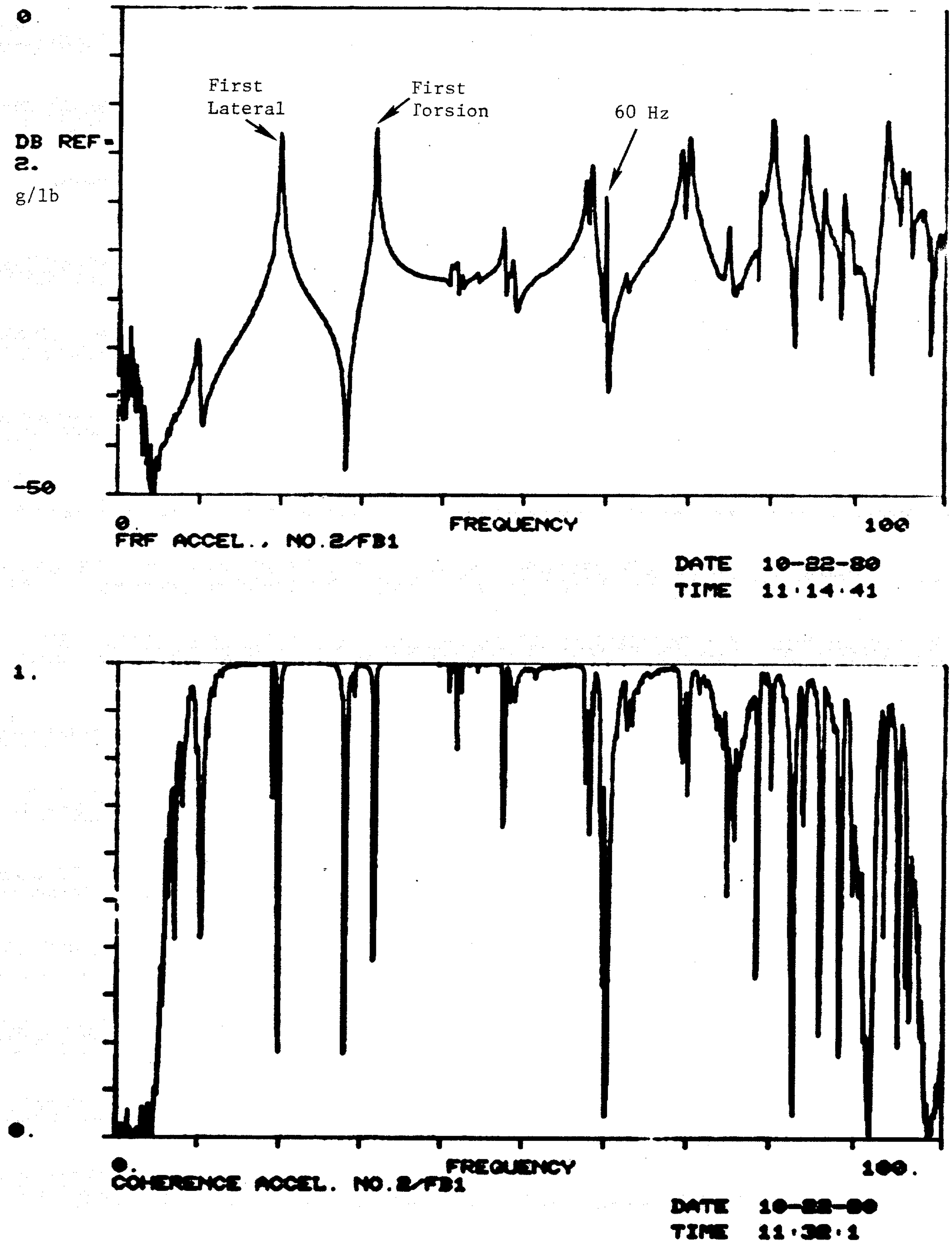


Figure 3.2 Frequency Response and Coherence for Accelerometer 2 Relative to Force F_B.

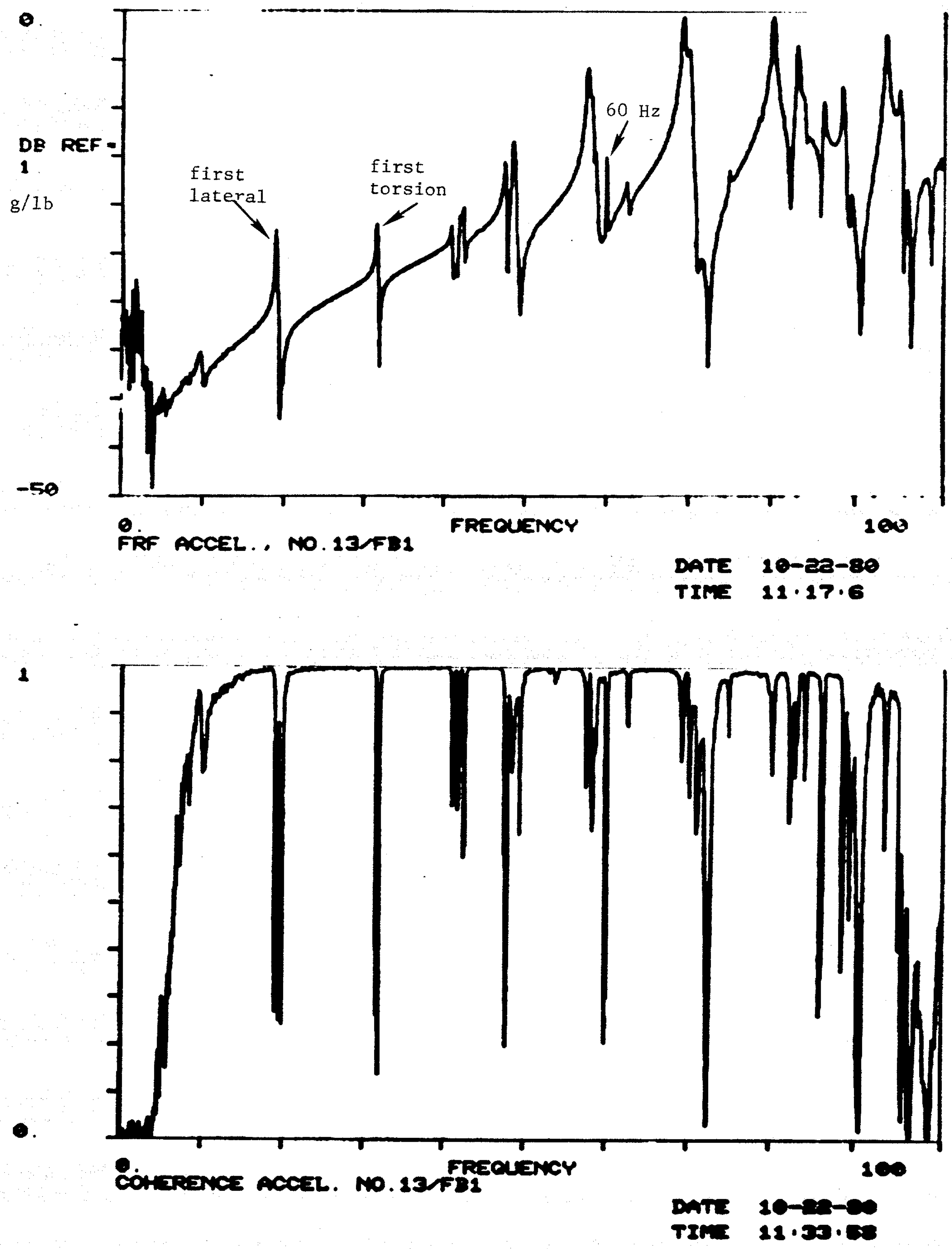
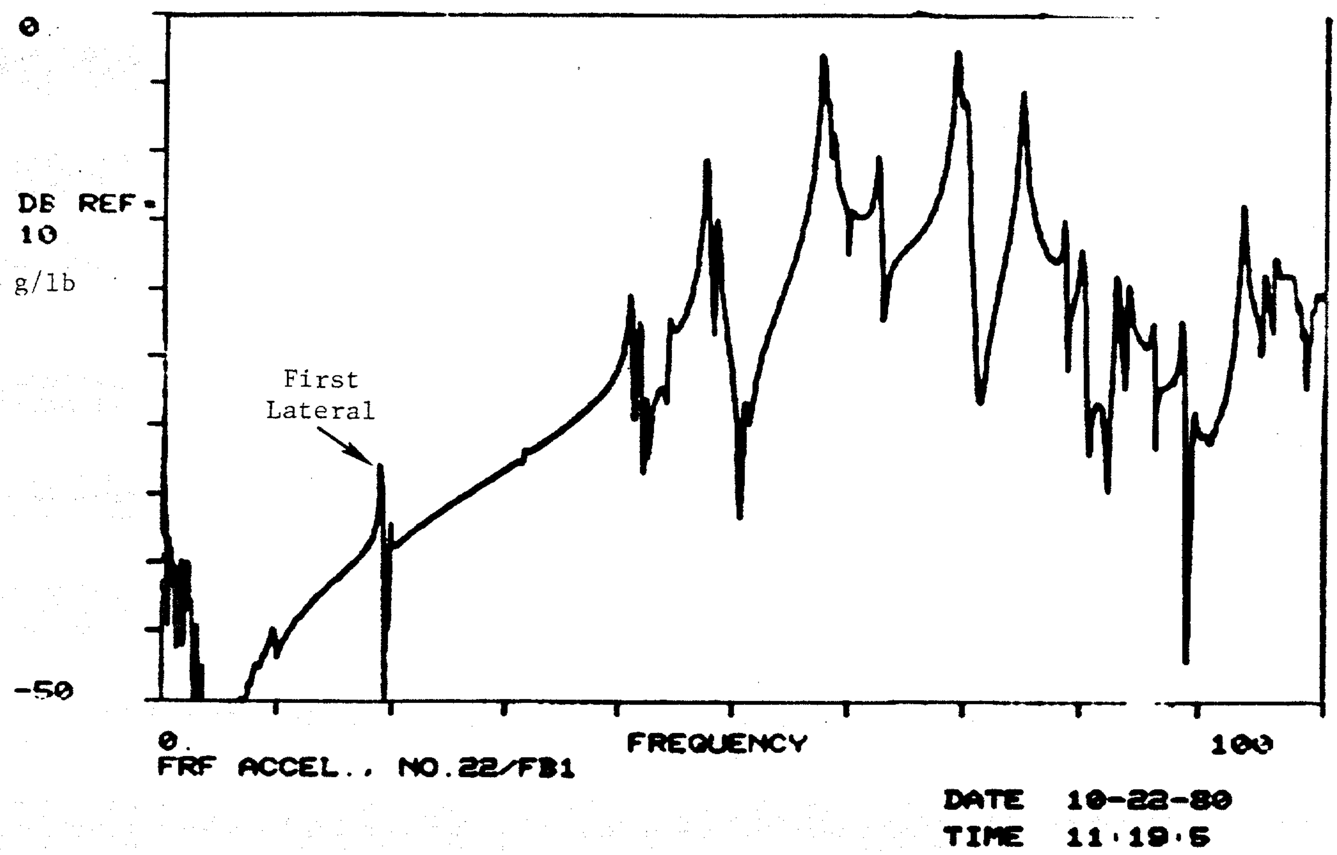


Figure 3.3 Frequency Response and Coherence for Accelerometer 13 Relative to Force F_B.



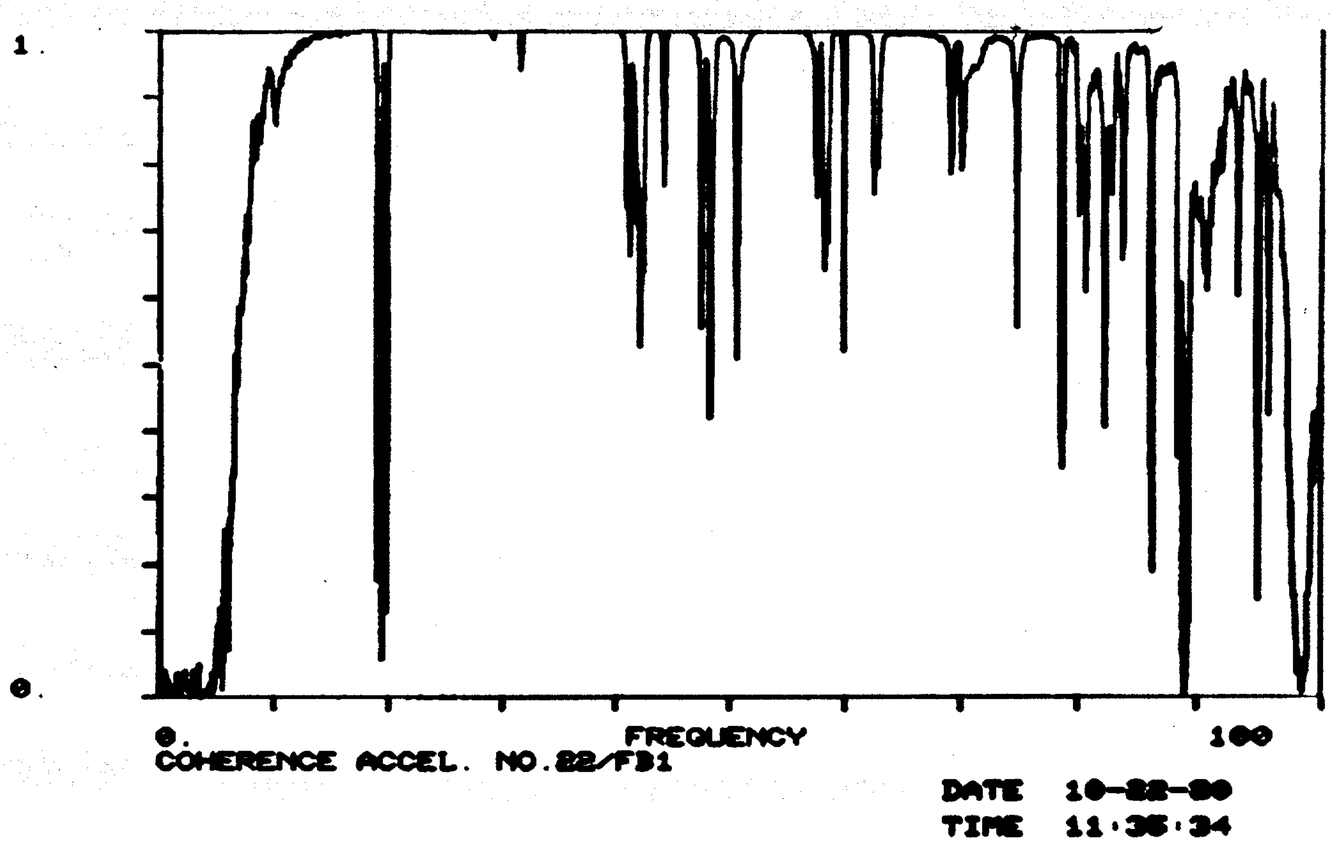


Figure 3.4 Frequency Response and Coherence for Accelerometer 22 Relative to Force F_B.

to collocate six accelerometers on two faces of a vertical stack of three 3/4-in. aluminum mounting cubes, positioned on the upper deck surface. The stack was placed at the Face 1/B corner and the accelerometers sensed X motion (see Figure 2.1). Data were acquired during F_A random excitation of the model and analyzed in exactly the same way as for the response data runs, except that one of the accelerometers was used as the reference signal for the frequency response (FRF) determinations.

A number of factors detracted from the precision of this calibration technique:

1. The motion was slightly different at the various positions on the block stack due to angular motions of the deck surface.
2. Since three-dimensional motion was taking place, unknown cross-axis sensitivity of the accelerometers influenced the results.
3. Random scatter was present in the frequency response amplitudes.

Known bias effects due to positioning on the cube stack are between 0 and 8%. Unknown cross-axis sensitivity contributions appear to be as high as about 8%, based upon observed trends in frequency response over the frequency range of the fundamental modes. Random uncertainty was of the order of $\pm 2\%$.

The net conclusion from this calibration effort is that it was unsatisfactory, the major factor being the cross-axis influences. Future efforts will require use of a shaker to uniaxially excite groups of accelerometers to determine both major axis and cross axis sensitivities. This could not be implemented for this phase of the Round Robin program, but will be pursued in future efforts.

3.4 Discussion of Results

The frequency response functions were processed for identification of modes identified in Section 4. A system identification scheme recently developed at The Aerospace Corporation (Ref. 2) was employed, as well as an independent analysis performed by the Structural Dynamics Research Corporation (SDRC) employing its commerically available software. The modal frequencies and dampings showed excellent consistency relative to the forcing position and relative to response location on the model. Mode shapes, however, showed significant inconsistencies. The reasons are unclear. The correspondence between the Aerospace and SDRC results was excellent.

It was decided to modify the run schedules for the damage scenario testing in an attempt to improve the mode shape reliability. This was done in two ways:

1. Sets of five accelerometers were defined for the data acquisition which enabled key mode shape results to be obtained from single data runs, rather than piecing information together from several runs.
2. Redundancy in acquiring key accelerometers data was added so that additional consistency checks would be made.

The net result was an increase in the data runs for the F_A forcing from 7 to 10 and no increase for the F_B forcing runs. No other changes were made for the damage scenario testing.

4. Mathematical Model

The structural dynamic model developed for the present study consists of a NASTRAN (Ref. 3) finite element description composed of a network of BAR elements representing the jacket structure and a rigid plate representing the honeycomb stiffened deck. Foundation constraints are assumed fully rigid. Nodal breakdown of a typical section, illustrated in Figure 4.1, is designed to permit accurate simulation of fundamental brace modes. Moreover, the consistent mass option is employed rather than lumped mass to further assure accuracy of such modes. The complete assembled finite element model is described in terms of 1626 grid degrees of freedom. Upon application of support constraints, rigid plate constraints and other dependency relationships, the dynamics of the structure are described in terms of 1488 degrees of freedom.

Normal mode analysis of the dynamic model was performed employing a new version of the subspace iteration technique (see Ref. 4 for description of the basic method) programmed specifically for the present study. This technique does not suffer from compromises in accuracy characteristic of Guyan reduction (Ref. 5) which could not be tolerated in the modal sensitivity evaluation.

Thirty-five modes of the structure were computed with natural frequencies below 101 Hz. The fundamental lateral modes at 22.55 and 22.61 Hz and the fundamental torsional mode at 33.77 Hz, illustrated in Figure 4.2, are the only overall beam-like lateral modes in the frequency range. The brace modes of primary interest for the modal sensitivity study are breathing modes (i.e. motion normal to faces) between 39 and 77 Hz. These modes are most simply described in terms of deformation patterns of horizontal members in a bay. Four classes of breathing modes are present, as shown in Figure 4.3, designated by the indices 01, 02, 02', or 03. Actually, various linear combinations of the 02 and 02' shapes occur because of the slight asymmetry caused by the two internal diagonals between levels 3 and 4, as seen in Figure 1.2. Thus, the designations 02 and 02' actually denote the lower and higher frequency mode of the pair having an 02, 02' combination. In addition, the modes occur in groups corresponding to predominant deformation in specific bays; for example a mode designated as 02/5 corresponds to lower frequency class 02 breathing most pronounced at level 5.

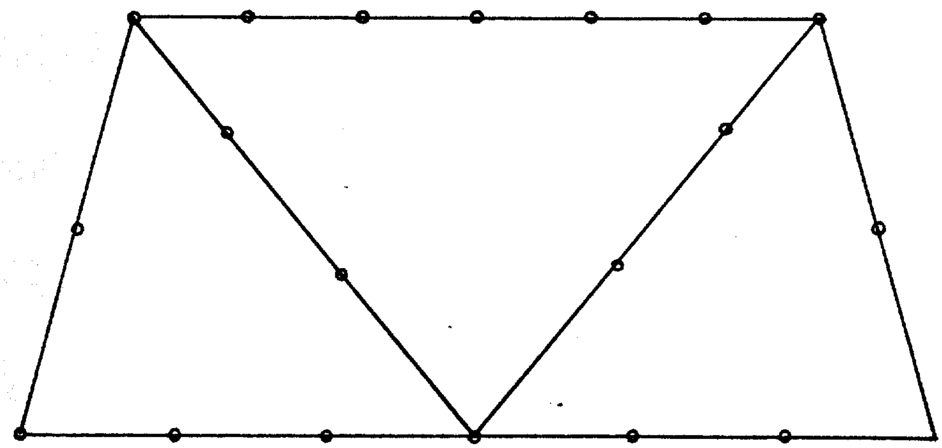


Figure 4.1 Nodal Breakdown of K-Brace Structure.

Mode 1 f = 22.55 Hz

Mode 2 f = 22.61 Hz

Mode 3 f = 33.77 Hz

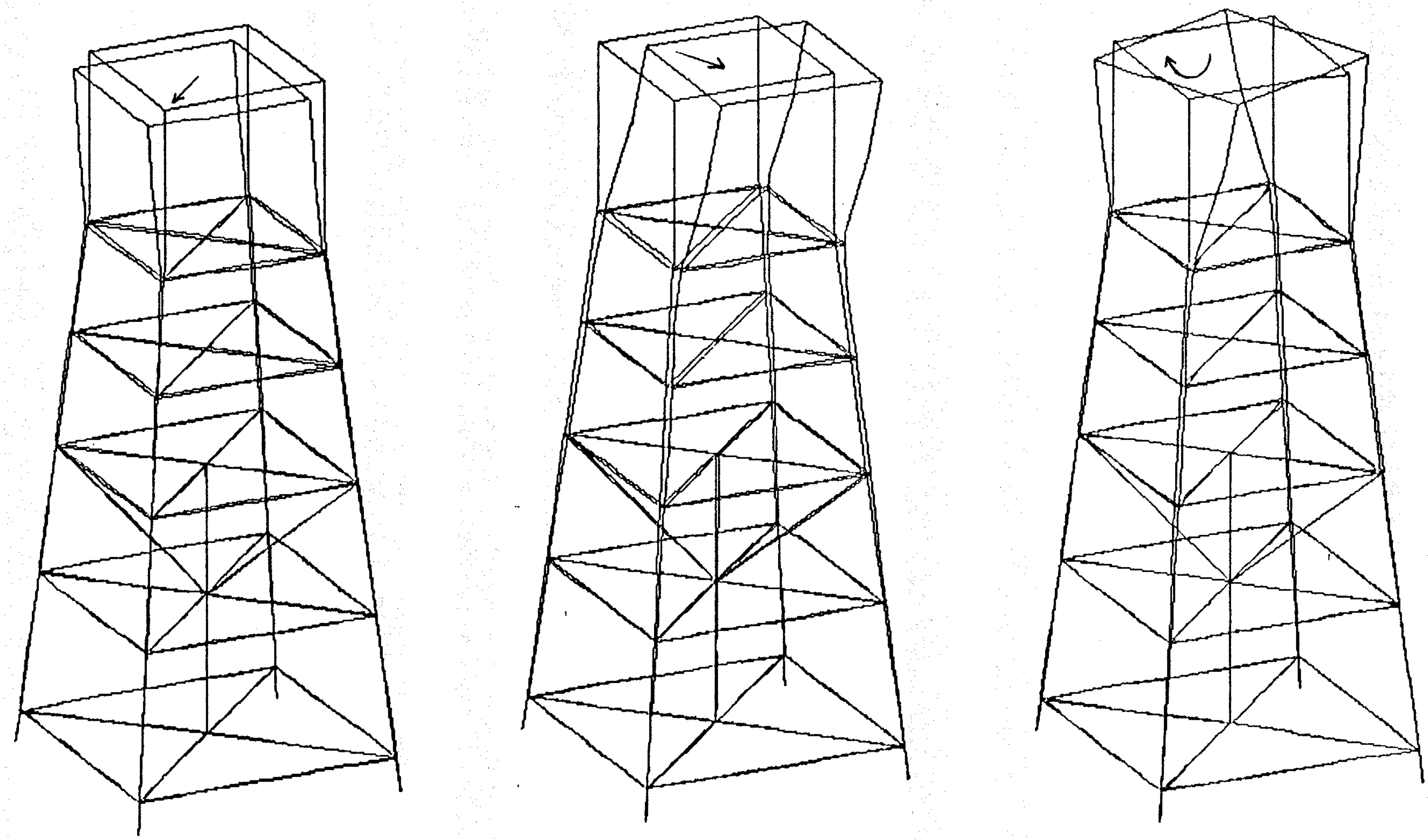


Figure 4.2 Fundamental Lateral and Torsional Modes From Mathematical Model.

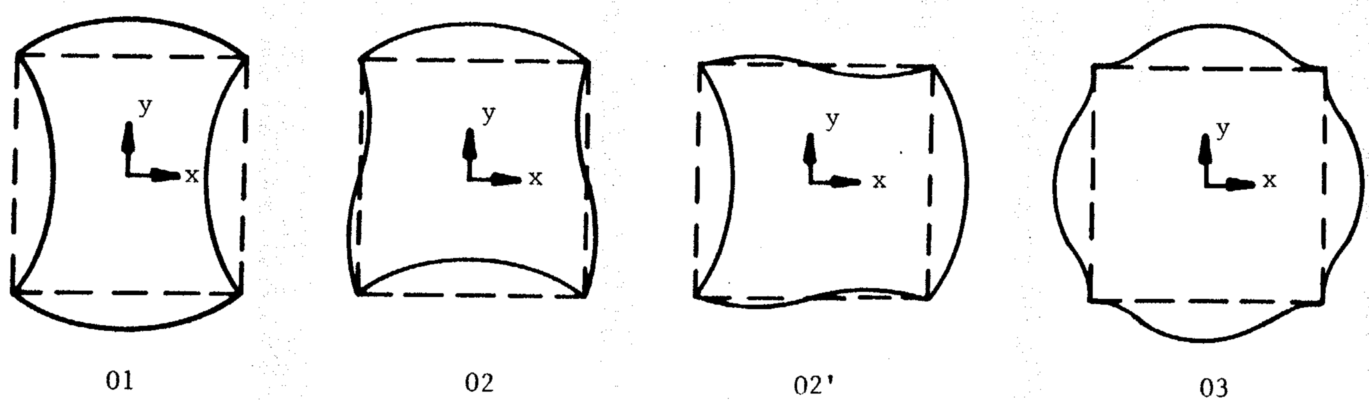


Figure 4.3 Brace Breathing Mode Classes.

A list of the selected modal frequencies below 77 Hz in Table 4.1 exhibits the fact that brace breathing modes are grouped in definite frequency ranges; i.e., 39.05 - 41.24 Hz for level 5, 45.29 - 50.94 for level 4, 56.53 - 63.73 for level 3, 69.04 - 77.02 Hz for level 2.

A typical brace mode shape, identified as predominantly associated with level 3 in the second shape family (02/3) with natural frequency of 57.72 Hz, is shown in Figure 4.4. (see Table 4.1, mode number 14). While the greatest amplitudes appear at level 3, it is seen that the 02 type shape pattern also appears at level 2 and 4. In fact the 02 shape appears at all levels, with the amplitudes diminishing with increased separation from the primary level. This propagation of the shapes also occurs for the 01 shape. The 03 shape does not propagate vertically because no net lateral force or individual leg torsion results from the vibration at the primary level (see Figure 4.3). It is the significant appearance of shapes 01 and 02 at level 1 (abovewater) that makes it possible to detect such lower level brace modes by excitation and measurement at level 1.

Natural frequencies obtained from baseline test data, for excitation at locations F_A and F_B are presented in Table 4.2 along with the mathematical model natural frequencies having shapes best corresponding to those of the test derived ones. The experimental frequencies for the fundamental lateral and torsional modes (i.e., 1Y, 1X, 1T) are 10 to 15% lower than the theoretical values. The corresponding experimental lateral mode shapes are almost exactly aligned in the X and Y axes, respectively, while the theoretical lateral mode shapes are aligned roughly 45 degrees with respect to the axes (see Figure 4.2). The directional discrepancy is not surprising in view of the very weak assymmetry of the mathematical model (due to a pair of interior diagonal members), thereby being easily overcome by construction irregularities in the physical model. Of greater significance is the disagreement in natural frequencies. Some insight into the source of disagreement is gained by comparing the mode shapes. Table 4.3 displays the test and predicted shapes normalized to level 1. The shapes below level 1 are in reasonable agreement. Greater flexibility in the "above water" section of the structure (i.e. D-L1) is, however, indicated from the test, possibly due to local flexibility of the honeycomb plate to main leg interface (not included in the math model).

Table 4.1 Natural Frequencies from Mathematical Model

Mode Number	Hz	Type
1	22.55	Lateral (x,-y)
2	22.61	Lateral (x,y)
3	33.77	Torsion
4	39.05	01/5
5	40.24	02/5
6	40.26	02'/5
7	41.24	03/5
8	45.29	01/4
9	47.51	02/4
10	47.58	02'/4
11	50.94	03/4
13	56.53	01/3
14	57.72	02/3
15	58.11	02'/3
16	63.73	03/3
18	69.04	02/2
19	69.39	02'/2
20	70.27	01/2
21	77.02	03/2

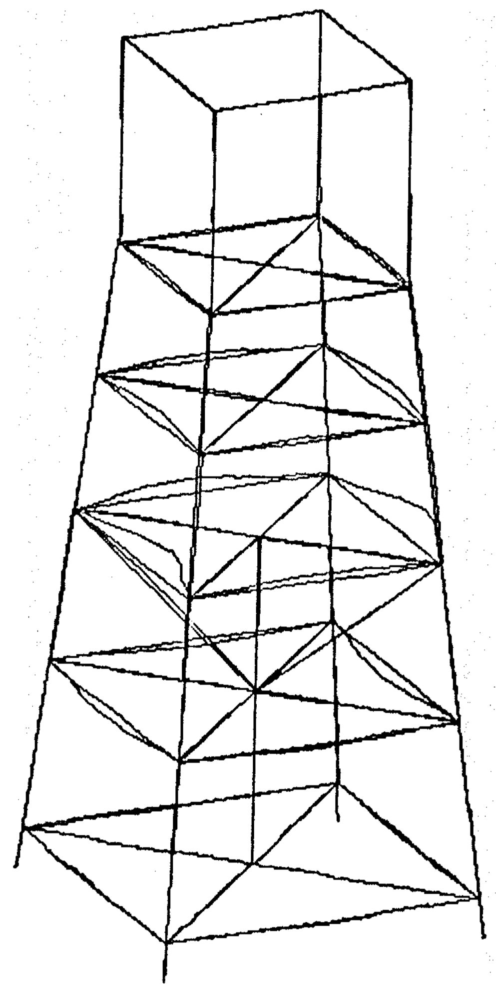


Figure 4.4 Brace Mode 02/3, f = 57.72 Hz

Table 4.2 Natural Frequencies from Baseline Test and Comparison to Mathematical Model

Mode	Test 1 (F_A)	Test 2 (F_B)	Math Model
1Y	19.12	19.10	22.55, 22.61
1X	19.88	19.86	
1T	31.72	31.65	33.77
01/5	40.97	41.04	39.05
01/4,03/4	44.43	44.39	--
01/4	47.58	47.58	45.29
02/4	48.5-.6	48.5-.6	47.51
02/3	57.61	57.64	57.72
02'/3	58.28	58.24	58.11
01/3	58.60	58.59	56.53
03/3	62.54	62.56	63.73
02/2	69.11	69.23	69.04
02'/2	70.34	70.12	69.39

Table 4.3 Comparison of Baseline Test and Mathematical Model Mode Shapes*
(Fundamental Lateral and Torsional)

	Lateral (Modes 1Y & 1X)		Torsional (Mode 1T)	
Deflection	Test	Math Model	Test	Math Model
Deck (D)	8.5	5.4	13.3	8.1
Level 1 (L1)	1.0	1.0	1.0	1.0
Level 2 (L2)	0.64	0.65	0.68	0.67
Level 3 (L3)	0.45	0.45	0.64	0.54
Level 4 (L4)	0.24	0.23	0.45	0.33
D-L1	7.5	4.4	12.3	7.1
L1-L2	0.36	0.35	0.35	0.33
L2-L3	0.19	0.20	0.04	0.13
L3-L4	0.21	0.22	0.24	0.21

*Normalized to unit deflection at Level 1. Level 5 not defined experimentally.

In general, good agreement between test deduced and mathematical model is indicated for the brace breathing modes in the 40 - 77 Hz frequency range. Families of test brace modes, at the various levels occur in proper frequency sequence (with respect to analytical predictions). The presence of non-symmetry in the test deduced brace modes (see Figure 4.5) is not surprising in view of close modal frequency spacing among the constituents of the brace mode families and the consequent sensitivity to construction irregularities.

At this point a judgment was needed to either adjust the mathematical model to conform to test data or to rely on the original theoretical model for sensitivity evaluations. Incorporation of local flexibility in the leg/deck interface would readily produce greater compatibility between the analytical and test deduced fundamental frequencies. However, adjustment of the jacket bracing model to conform to the associated test mode shapes appeared to be a major undertaking and would likely produce non-unique results. In view of already known uncertainties with the measured mode shapes (see Section 3), it was decided that no adjustments would be made to the mathematical model. General trends in modal sensitivity to brace failures and other changes are believed similar between the mathematical model and actual structure.

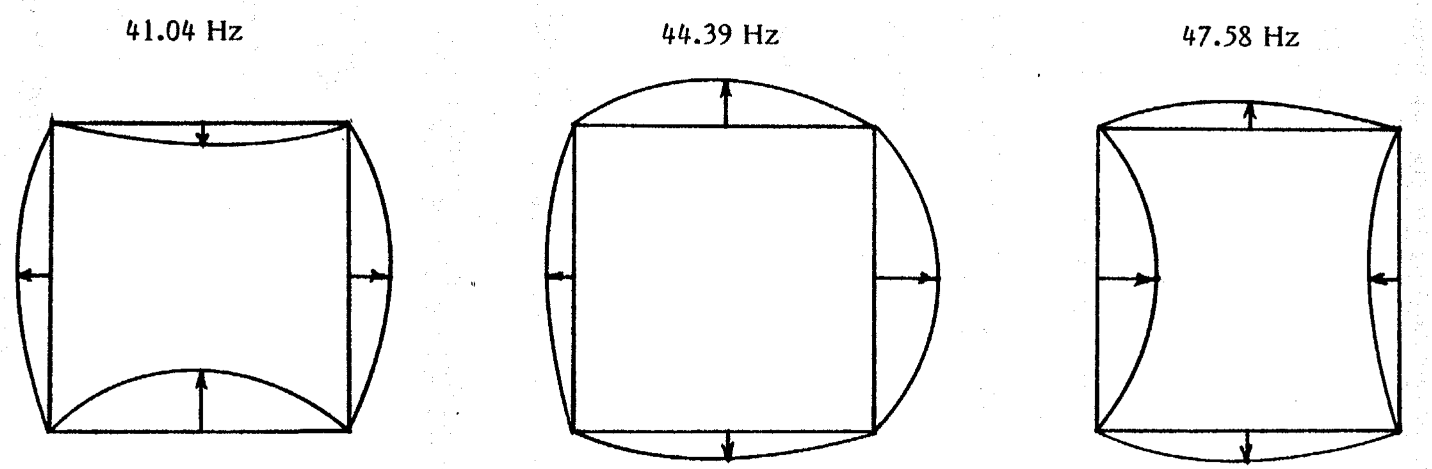


Figure 4.5. First Three Experimentally Deduced Breathing Modes As Observed at Level 1 in Test 2 (See Table ..2).

5. Modal Sensitivity Analysis

Sensitivity of the baseline mathematical model to a variety of single member severances and mass changes was investigated to provide guidance for damage scenario discrimination. In the case of single member severances, the efficient analysis technique developed during the SP-62C study (Ref. 6) was employed for thirteen damage scenarios. The damage cases consisted of six diagonal brace severances, six horizontal brace severances, and one main leg severance near the foundation (interpreted as a local foundation failure). In addition, three mass change cases were treated by re-analysis of the full 1488 degree-of-freedom model: (1) a 10% increase in deck mass concentrated at the geometric center of the deck, (2) a 10% increase in deck mass concentrated at the B-1 deck corner, and (3) simulated marine growth on all four legs between levels 1 and 2 modeled as added mass per unit length of 0.62 lb/ft (118 lb/ft full scale), corresponding to a growth thickness equal to the radius of the leg.

Evaluation of sensitivity trends is performed from three separate viewpoints which are (a) general frequency sensitivity of the fundamental lateral and torsional modes, (b) mode shape sensitivity of fundamental lateral and torsional modes, (c) frequency sensitivity of the brace mode families. The final category is considered useful for qualitative trends observed from resonant response of above water (level 1) horizontal brace accelerations. The data observed in category (b) represents the basis of our flexibility monitoring concept.

A summary of frequency sensitivities of the fundamental lateral and torsional modes is presented in Table 5.1. Directionality of the pair of lateral modes, which is discernable with above water accelerometers, is also indicated in the table. The following characteristics are observed regarding frequency sensitivity and lateral mode directionality of the subject structure:

(1) Directionality of the lateral modes, originally aligned $\pm$ 45° with respect to the x-axis, become roughly aligned with the x and y axes, respectively, when a brace member is severed.

TABLE 5.1 Sensitivities of Lateral and Torsional Modal Frequencies

CHANGE TYPE	LOCATION	LATERAL MODE 1	LATERAL MODE 2	TORSIONAL MODE
Diagonal Brace Severances	Face 1, L4/5	-2.1* (y)	0 (x)	-2.3
	Face 1, L3/4	-1.3 (y)	0 (x)	-1.6
	Face 1, L2/3	-1.3 (y)	0 (x)	-1.4
	Face 1, L1/2	-8.4 (y)	0 (x)	-4.2
	Face 2, L2/3	-1.3 (y)	0 (x)	-1.4
Horizontal Brace Severances	Face 1, L5	0 (y)	0 (x)	0
	Face 1, L4	-0.5 (y)	0 (x)	-0.5
	Face 1, L3	-0.2 (y)	0 (x)	-0.3
	Face 1, L2	-1.8 (y)	0 (x)	-1.2
	Face 2, L5	0 (y)	0 (x)	0
Main Leg Bottom Release	B-1 Corner, L4/5	-15.3 (-x,y)	0 (x,y)	0
+10% Deck Mass	Center	-2.9 (-x,y)	-2.8 (x,y)	0
	B-1 Corner	-2.9 (-x,y)	-2.9 (x,y)	-2.9
Marine Growth	All Legs, L1/2	-0.4 (-x,y)	-0.3 (x,y)	-0.3

*Percent change in frequency from baseline.

(2) Severance of a diagonal brace produces a reduction in frequency of the lateral mode associated with the direction for which the brace provides stiffness, as well as a reduction in the torsional mode frequency; reduction in frequency is on the order of 1-2% for the affected lateral mode and torsional modes except for a diagonal brace severance in level 1/2 which yields a significantly larger reduction. No frequency reduction occurs in the lateral mode for which the severed brace does not provide stiffness.

(3) Severance of a horizontal brace produces trends similar to those observed for diagonal brace severances, but with much lower frequency sensitivity (on the order of 0 - 0.5%, except for level 2 which produces 1 - 2% frequency sensitivity).

(4) Removal of main leg bottom support produces a large reduction in lateral mode frequency (15%) for a mode with motion aligned with the affected leg and the leg diagonally opposite. The other lateral mode and the torsional mode experience negligible frequency change.

(5) Mass changes tend to produce roughly the same frequency sensitivity in both lateral modes. When the mass change affects the torsional mass moment of inertia, the torsional mode frequency is affected as well.

In summary, the contrast among (1), (4) and (5) permits discrimination between member severance and mass change and between main leg (or foundation) and brace severances. Moreover, for the case of a brace severance, the direction associated with the affected lateral mode indicates that a failure has occurred on one of two faces (i.e., if "y" mode frequency is reduced, the severance has occurred on either face 1 or 2; if "x" mode frequency is reduced, the severance has occurred on either face A or B). For a main leg bottom support loss, the direction of the affected lateral mode indicates a failure in one of two legs through which the motion vector is directed.

Additional information for location of the face on which a diagonal brace has been severed is contained in modal deflections of legs immediately above the waterline (level 1). Analytical mode shapes indicate that displacement of the affected face is on the order of 20% greater than that of the opposite face in the lateral mode with reduced frequency; moreover the torsional mode exhibits a similar trend. An example of these trends for a level 4/5 diagonal brace severance is given in Figure 5.1. These shape sensitivity trends are also present at the deck level, but to a lesser extent than at level 1.

In order to locate the region at which brace member severance has occurred, mode shape data below the waterline must be employed. A simplified relationship which expresses the local bay flexibility characteristics, is obtained on the assumption that the tower behaves as a shear beam with primary inertia at the deck level when the structure is responding in the fundamental lateral and torsional modes. The non-dimensional coefficient, $(x_n - x_{n+1})/x_d$, for average motion in the "x" direction expresses the flexibility of the bay between levels "n" and "n+1"; similar coefficients describe flexibility in the "y" and "T" directions. The summary of "y" mode shape and flexibility coefficients presented in Tables 5.2 (illustrated in Figure 1.4) and 5.3 for Face 1 diagonal and horizontal brace severances, respectively, illustrates the ability of such flexibility parameters to locate the bay in which member severance has occurred. For diagonal brace severance, the flexibility parameter of the affected bay in the appropriate lateral (or torsional) mode increases on the order of 100% or greater, while the flexibility parameters of the other bays are relatively unaffected (see Figure 1.4). In the case of horizontal brace severance, flexibility increases on the order of 10 - 30% are noted for the affected bay with the remaining bays exhibiting no sensitivity. The mode shapes and flexibility coefficients are relatively insensitive to deck mass and simulated marine growth mass changes. Thus, flexibility monitoring also provides capability for discrimination between structural damage and benign changes. The above technique of assessing bay flexibility sensitivity while relatively insensitive to deck mass changes can be expressed, alternatively, in terms of a ratio of underwater bay flexibility to abovewater structure flexibility [i.e., $(x_n - x_{n+1})/(x_d - x_1)$]. This technique is potentially less sensitive to deck mass change since the relative deflection "$x_d - x_1$" is directly proportional to the dynamic shear force associated with deck inertia (to a first-order approximation).

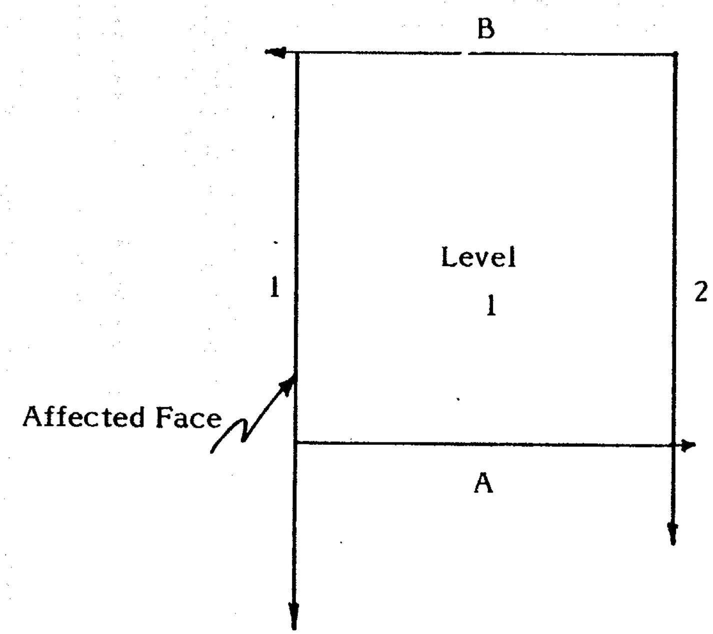


Figure 5.1 Lateral Mode Indicating Face 1 Diagonal Brace Severance.

TABLE 5.2 "Y" Lateral Mode Sensitivity To Face 1 Diagonal Failures

		Baseline	L5	L4	L3	L2
	Hz	1.635	1.599 (-2.1%)	1.612 (-1.3%)	1.612 (-1.3%)	1.496 (-8.4%)
MODE SHAPE	D	1.000	1.000	1.000	1.000	1.000
	L1	0.184	0.227	0.209	0.220	0.252
	L2	0.120	0.170	0.149	0.160	0.101
	L3	0.083	0.140	0.115	0.081	0.067
	L4	0.042	0.108	0.043	0.042	0.036
	L5	0.008	0.012	0.007	0.008	0.007
BAY (DEFL)	D-L1	0.816	0.773	0.792	0.780	0.748
	L1-L2	0.065	0.057	0.060	0.060	0.151 (132%)
	L2-L3	0.037	0.030	0.034	0.080 (117%)	0.034
	L3-L4	0.041	0.032	0.072 (77%)	0.038	0.031
	L4-L5	0.035	0.096 (175%)	0.036	0.034	0.029

TABLE 5.3 "Y" Lateral Mode Sensitivity to Face 1 Horizontal Failures

		Baseline	L5	L4	L3	L2
Hz		1.635	1.633 (0%)	1.626 (-0.5%)	1.631 (-0.2%)	1.605 (-1.77%)
MODE SHAPE	D	1.000	1.000	1.000	1.000	1.000
	L1	0.184	0.186	0.193	0.190	0.198
	L2	0.120	0.122	0.130	0.126	0.113
	L3	0.083	0.086	0.095	0.080	0.077
	L4	0.042	0.047	0.047	0.042	0.041
	L5	0.008	0.008	0.008	0.008	0.007
BAY (DEFL)	D-L1	0.816	0.814	0.807	0.810	0.802
	L1-L2	0.065	0.064	0.063	0.065	<u>0.085</u> (31%)
	L2-L3	0.037	0.036	0.036	<u>0.046</u> (24%)	0.036
	L3-L4	0.041	0.039	<u>0.052</u> (28%)	0.038	0.036
	L4-L5	0.035	<u>0.039</u> (12%)	0.035	0.034	0.034

Study of the effect of structural failures on local brace modes indicates change trends which are not necessarily limited to modes dominant in the affected bay. A limited assessment of structural change can be made with abovewater instrumentation on the level 1 horizontal braces. Local brace modal frequencies are detectable in such locations and shifts in higher mode frequencies and possibly changes in response levels may indicate the presence of structural damage. Localization of the damage to face is probably unreliable.

The overall conclusions of this modal sensitivity study are:

(1) Observation of natural frequency changes in the fundamental lateral and torsional modes provides some basis for discrimination of member failure conditions and mass changes.

(2) Observation of abovewater mode shape sensitivity of the fundamental lateral and torsional modes gives evidence of the face on which a diagonal brace has been severed, or the candidate corners associated with loss of main leg bottom support.

(3) Flexibility monitoring of fundamental lateral and torsional mode shapes provides the most effective means for location of diagonal and horizontal severances.

(4) Abovewater observation of local brace mode frequency shifts and associated shape changes provides a qualitative indication of brace failures.

6.0 Damage Assessments

The four damage scenarios were evaluated in a blind manner on the basis of frequency responses supplied for accelerometers 1-15 and 29-32 (see Figure 2.1 for locations). The other accelerometers were not employed in our evaluations. Assessment of damage was made by identification of modal parameters within the three categories enumerated in Section 1.5. These are: (1) analysis of abovewater positions 1-6 for the three fundamental mode frequencies and shapes, (2) analysis of abovewater and underwater leg positions 1-15 for more extensive definition of fundamental mode shapes, and (3) analysis of abovewater positions 29-32 for identification of natural frequencies of normal-to-face brace modes. Evaluation of modal parameters was performed with a unique data analysis scheme developed at The Aerospace Corporation (Ref. 2).

The following discussion provides the rationale employed in identification of the damage scenarios. The damage evaluation forms submitted to the Test and Evaluation Agent are reproduced in Appendix B. The data was received by us on 24 March 1981 and the completed forms returned by us on 22 May 1981, thereby meeting the pretest goal of responding within a two-month period.

The modified data groupings, mentioned at the end of section 3, substantially improved the reliability of the fundamental mode shapes for the damage scenario tests relative to the baseline tests. A careful review of the data led to the conclusion that the damage scenario #2 results for the fundamental mode shapes were the most reliable baseline reference.

While several anomalies in measured frequency response were encountered, redundant acquisition of the data enabled avoidance of misleading information.

6.1 Damage Scenario 1.

6.1.1 Abovewater Accelerometers, Fundamental Modes

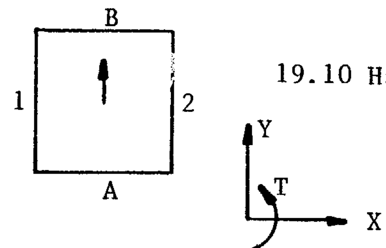
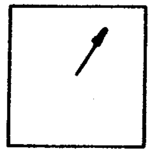
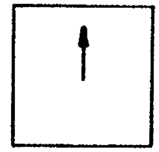
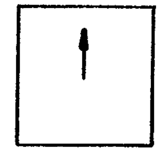
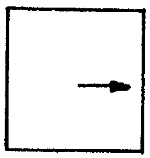
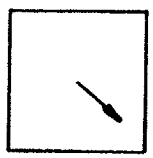
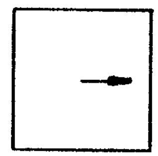
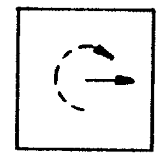
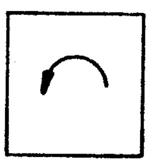
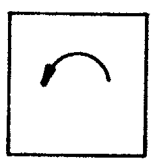
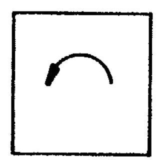
The observables in the fundamental mode group employing abovewater accelerometers, consist of (a) natural frequency change, (b) overall jacket/foundation flexibility change, expressed in terms of the ratio of level 1 deflection to above water relative deflection (e.g., $Y_1/(Y_d-Y_1)$ for y directed motion); and (c) torsional/lateral coupling, expressed in the predominantly lateral modes as the ratio of torsional to dominant lateral motion at level 1 and in the predominantly torsional mode as the inverse of this ratio. With reference to the positions and directions of accelerometers indicated in Figure 2.1, the following convention is adopted for the lateral and torsional net displacement quantities (where a_i is the acceleration at position i):

$$\text{deck -}\quad \begin{cases} X_d = (a_2 + a_3)/2 \\ Y_d = a_1 + (a_2 - a_3)/2 \\ T_d = a_2 - a_3 \end{cases}$$

$$\text{level 1}\quad \begin{cases} X_1 = (a_5 + a_6)/2 \\ Y_1 = a_4 + (a_5 - a_6)/2 \\ T_1 = a_5 - a_6 \end{cases}$$

The fundamental mode findings for the baseline and damage scenarios 1-4 are summarized in Table 6.1. For damage scenario 1, the roughly 10% reduction in one lateral mode frequency, as well as its directionality nearly across corners, accompanied by relative frequency insensitivity of the other two fundamental modes clearly indicates a foundation failure. This frequency sensitivity is predicted by analysis, as shown in Table 6.2. The roughly 140% increase in overall jacket/foundation flexibility in the affected mode (0.29 versus 0.12 on Table 6.1) adds to the evidence of a foundation failure. The directionality of the first mode points to a failure at the foundation of either the A-1 or B-2 leg. Identification of the particular leg should have been possible if reliable results for the upward directed accelerometers (17-20)

TABLE 6.1. FUNDAMENTAL MODES, ABOVEWATER TEST PARAMETERS

BASELINE & DS-4	A1 OR B2 BOTTOM FAILURE (DS-1)	NO SIGNIFICANT FAILURE (DS-2)	FACE B DIAGONAL SEVERANCE (DS-3)
 19.10 Hz $Y_1/(Y_d-Y_1)$ = 0.12 T_1/Y_1 = 0.03	 17.48 Hz (-10.3%)* 0.29 0.00	 19.10 Hz (0%) 0.12 0.11	 19.10 Hz (0%) 0.12 0.07
 19.86 Hz $X_1/(X_d-X_1)$ = 0.08 T_1/X_1 = -0.17	 19.48 Hz (0%)* 0.12 -0.14	 19.85 Hz (0%) 0.10 -0.20	 19.60 Hz (-1.3%) 0.14 -0.35
 31.68 Hz $T_1/(T_d-T_1)$ = 0.07 X_1/T_1 = -0.10	 31.52 Hz (-0.5%) 0.09 -0.05	 31.64 Hz (-0.1%) 0.08 -0.07	 31.08 Hz (-1.9%) 0.12 -0.32

*AVERAGE BASELINE FREQUENCY USED: (19.10 + 19.86)/2 = 19.48 Hz

Table 6.2 Flexibility Parameters, Theory and Test

Mode		Baseline		Foundation Failure		L4-5 Diagonal Severance	
		Theory	Test(DS-2)	Theory	Test(DS-1)	Theory	Test(DS-3)
	Frequency (Hz)	22.61	19.10	19.10(-15.3%)	17.48(-10.3%)*	22.58(-0.1%)	19.10(0%)
Y lateral	Bay 1-2	0.080	0.060	0.142	0.097	0.079	0.054
	Bay 2-3	0.045	0.019	0.114	0.059-0.072	0.045	0.018
	Bay 3-4	0.050	0.021	0.127	0.044-0.058	0.045	0.021
	Below 4	0.051	0.024	0.142	0.073	0.051	0.025
	Frequency (Hz)	22.55	19.86	22.61(0%)	19.48(0%)*	22.08(-2.1%)	19.60(-1.3%)
X lateral	Bay 1-2	0.080	0.032	0.084	0.035	0.074	0.031
	Bay 2-3	0.045	0.020	0.048	0.027	0.039	0.017
	Bay 3-4	0.050	0.023	0.043	0.030	0.041	0.017
	Below 4	0.051	0.028	0.054	0.042	0.139(173%)	0.075(168%)
	Frequency (Hz)	33.77	31.64	33.35(-1.2%)	31.52(-0.4%)	33.00(-2.3%)	31.08(-1.8%)
torsion	Bay 1-2	0.046	0.026	0.046	0.029	0.041	0.024
	Bay 2-3	0.019	0.003	0.019	0.005	0.016	0.001
	Bay 3-4	0.030	0.018	0.030	0.016	0.037	0.009
	Below 4	0.046	0.034	0.047	0.044	0.103(124%)	0.090(165%)

*Average of baseline lateral frequencies, 0.5(19.10 + 19.86) = 19.48, used as the reference frequency.

had been made available. Unfortunately, reliable results were not available due to missing data in the package supplied to us for damage scenario 1.

6.1.2 Abovewater and Underwater Leg Accelerometers, Fundamental Modes

The frequency and directionality information deduced from underwater accelerometers substantiates that obtained from abovewater accelerometers. Table 6.2 contains the flexibility parameters from both theory and test and Figure 6.1 is a graphical display of the test flexibility parameters. Note from Figure 6.1 that there is a large increase in all of the indicated flexibilities in the Y-lateral mode (at 17.48 Hz, see Table 6.1). This behavior is indicative of a leg bottom failure. The mechanism for apparent flexibility increase in the case of leg failures differs substantially from the case of a diagonal brace failure. In addition to a local shear flexibility increase, severence of a leg introduces a local "hinge" flexibility which produces an increase in apparent shear flexibility in all stations above the failure.

6.1.3 Abovewater Positions, Brace Modes

For the damage scenario in question, analysis of brace mode data with abovewater instrumentation does not add to the above described judgments. Investigation of fundamental lateral and torsional mode sensitivity is sufficient for identification of damage scenario 1.

6.2 Damage Scenario 2

6.2.1 Abovewater Accelerometers, Fundamental Modes

The fundamental mode parameters deduced for damage scenario 2 from abovewater accelerometers appear in Table 6.1. While some change is noted in abovewater shape parameters, the lack of frequency shift in all three fundamental modes indicates that diagonal or leg severance has not occurred, nor have there been any significant mass changes. The apparent changes noted in mode shape parameters are within the range of uncertainty of the baseline test data.

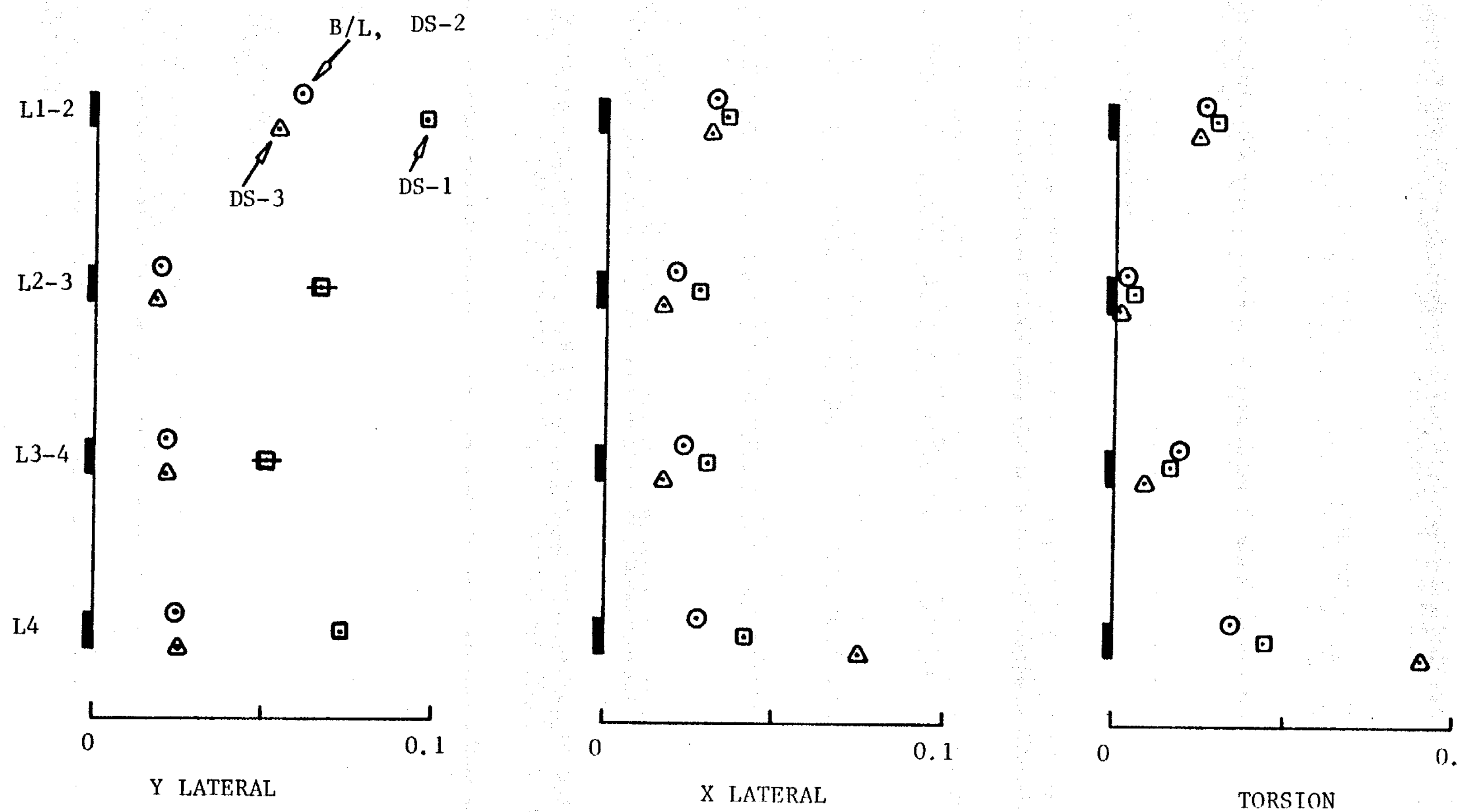


FIGURE 6.1 TEST FLEXIBILITY PARAMETERS

6.2.2 Abovewater and Underwater Leg Accelerometers, Fundamental Modes

After careful review of the fundamental mode shape parameters, it was concluded that the fundamental mode shapes associated with damage scenario 2 provided the most reliable baseline mode shape parameters.

6.2.3 Abovewater Accelerometers, Brace Modes

Accelerometers 29-32 (abovewater positions) were employed to detect the brace modes in the 40 to 70 Hz range. The only noticeable frequency shift was a 1% increase in a 41-Hz mode. This is the 01/5 mode (as seen in Table 4.2), associated with activity predominant at level 5 (that is, in the group of lowest K-brace sections). Other evidence of change is an observed shift in the degree of amplitude participation of several modes within the 40-43 Hz range of the frequency response functions with respect to baseline results. This frequency range contains the modes associated predominantly with the lowest K-braces. This is, therefore, additional support for a structural change in this region of the structure.

Possibilities for the cause of the observed changes are (1) severance of one or more horizontal members at level 5, (2) partial severance in one or more of the lowest bay K-brace sections (in horizontals or diagonals or both), (3) a mass change to one or more brace members in the lowest bay group, such as due to simulated flooding, or (4) a minor change in foundation support.

We had full confidence that structural change had been detected. As to the identification of structural failure as the cause, we could not distinguish between a failure or a nonfailure change. We consequently, assigned a 50 percent confidence to a failure diagnosis.

Since brace mode information is based upon abovewater accelerometers only, there is no basis for identifying the face in which the possible failure occurred.

6.3 Damage Scenario 3

6.3.1 Abovewater Accelerometers, Fundamental Modes

The fundamental mode parameters deduced for damage scenario 3 from abovewater accelerometers are summarized in Table 6.1. Reduction in x-lateral and torsional mode frequencies of 1.3% and 1.9%, respectively, accompanied by no change in y-lateral mode frequency indicate the presence of a diagonal brace severance on the A or B faces, or possibly a horizontal brace severance at level 2 on the jacket. Horizontal member failures below level 2 are ruled out from consideration since theoretical results predict nearly undetectable frequency changes in the fundamental mode group. Coupling of torsional and x-lateral motions in the affected modes exhibits greater flexibility of face B (especially in the torsional mode) pointing to the presence of a severance on face B, rather than on face A. All of the above noted judgments are consistent with predictions from analytical sensitivity studies.

Further speculation as to location of the member failure and the member type are made strictly by comparison to analytical sensitivity study data. Diagonal brace failure between level 1 and level 2 is not indicated due to smallness of frequency changes (roughly 8% lateral and 4% torsional mode frequency reductions are predicted for such a case). The greater torsional frequency reduction than lateral frequency reduction implies that a horizontal brace severance at level 2 has not occurred (1.8% lateral and 1.2% torsional natural frequency reductions are predicted for such a case).

The net assessment, based on abovewater identification of fundamental modes and analytical sensitivity results, is severance of one or both diagonals in a single bay below level 2 on face B. The severance of two diagonal braces in a single K-brace theoretically produces the same sensitivity in the fundamental mode group as a single diagonal brace severance since the shear stiffness of the affected face is reduced by the same degree for both cases.

6.3.2 Abovewater and Underwater Leg Accelerometers, Fundamental Modes

All of the above judgments made for damage scenario 3 are substantiated by underwater leg accelerometer data. Individual jacket bay flexibility parameters for the fundamental mode shape group are presented in Table 6.2 and plotted in Figure 6.1. These parameters clearly indicate a diagonal brace severance in the level 4-5 bay due to drastic increases in flexibility of that bay in the x-lateral and torsional modes, as predicted by the sensitivity analysis. Thus, it is positively concluded that a diagonal brace severance (in one or both braces) has occurred on face B at the level 4-5 bay in damage scenario 3.

6.3.3 Abovewater Accelerometers, Brace Modes

No further assessment was called for in identification of damage scenario 3. Thus, brace mode sensitivity was not investigated for this case.

6.4 Damage Scenario 4

No data analysis was required for damage scenario 4 since the frequency response functions were numerically identical to the baseline test case functions. It is positively concluded that no damage or other changes are present in this case.

7.0 Conclusions

Each of the three techniques utilized to interpret the damage scenarios proved to be useful. The type of failure for the two cases of significant damage (scenarios 1 and 3) was correctly identified by global mode monitoring. A degree of localization was also possible. Flexibility monitoring substantiated these findings and enabled an improved localization of the damage. Global mode monitoring correctly led to the conclusion of no significant damage for scenario 2, while the local mode monitoring technique led to the 50-percent confident identification of partial horizontal or vertical brace failure in a lowest bay.

The parametric changes observed from the damage cases were in satisfactory agreement with the sensitivity results predicted by the mathematical model of the structure. This was true even though the actual fundamental natural frequencies were significantly low due to suspected missing rotational flexibility at the leg/deck interfaces in the mathematical model. This confirmed our belief that fine adjustment of the mathematical model to match the baseline results was not essential.

Global mode monitoring of the fundamental modes is effectively embodied within flexibility monitoring and provides useful supporting data. The six abovewater accelerometers utilized for the global mode technique were included in the fifteen accelerometer positions utilized for flexibility monitoring. Moreover, the data analysis for the flexibility parameters involved spectral analysis from which the fundamental natural frequencies can also be derived.

Based upon the success in the blind testing, the favorable mathematical sensitivity results, and our prior field experience on the SP-62C platform (Reference 1), flexibility monitoring appears to be a most attractive technique for field evaluation. Additional analytical and laboratory studies of local mode monitoring are required before its feasibility can be thoroughly assessed.

8.0 Recommendations

Additional special testing of the model should be conducted in preparation for field testing of the flexibility monitoring method (this has been authorized and half completed at the time of this writing, 30 November 1981).

Field testing of flexibility monitoring should be conducted on existing platforms which have been outfitted with chutes and for which instrument packages have been developed by industry. The most immediate candidates are the Chevron Garden Banks and the Shell Cognac, Bourbon, Ellen and Ellie platforms for which instrument packages are imminently available. When instrument packages are developed for the wet chutes on the Union Cerveza platform, this structure will also become a candidate for field testing.

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APPENDIX A

DAMAGE PLAN

APRIL 1980

NDE ROUND ROBIN

THE EVALUATION OF NDE TECHNIQUES FOR DETERMINING OFFSHORE STRUCTURES INTEGRITY

STRUCTURAL MECHANICS PROGRAM
OFFICE OF NAVAL RESEARCH

RESEARCH AND DEVELOPMENT PROGRAM FOR
OUTER CONTINENTAL SHELF OIL AND GAS OPERATIONS
U.S. GEOLOGICAL SURVEY

PREFACE

Most new technologies arise from the need to accomplish something for the first time or to improve the economics, safety, or useability of existing methods. Nondestructive testing or nondestructive examination (NDE), as it is now called, has been developed for both these reasons. Over the last two decades, there has been considerable activity in the development of many NDE techniques to determine the vibration characteristics, functional life expectancy, and integrity of various kinds of structures subjected to all kinds of deterioration. The increased use of lighter, high strength materials and those used in harsh and inaccessible environments dictated more precise inspection and monitoring techniques.

In the field of offshore structures, the predominant method of structural examination is visual inspection above and below water for signs of deterioration such as cracked welds and broken braces. The costs of diving and submersible operations in the unfriendly environment of the North Sea, for example, is very expensive and has consequently stimulated the development of alternative means for assuring structural integrity. Two approaches are being pursued. Offshore operations are being studied from the considerations of the risks and probabilities of failure, and remote inspection and monitoring techniques are being evaluated to provide continuing reassurances of safe operations.

Each NDE technique proclaims some unique improvement, and needs to be quantified and documented for most underwater applications. Some techniques appear to require no underwater sensors, whereas others purport to predict structural life, and so on. There are many advocates, ranging from those which approach NDE from an academic point of view to private companies who are in the business of inspection and monitoring. Because industries and governments on both sides of the Atlantic are increasingly interested in the furtherance of NDE from both a safety and an economic standpoint, and since much progress has been accomplished already, the time is right to assess the applicability of the various techniques.

This program, the NDE Round Robin, has been formulated to focus, evaluate, and document the NDE activities of its sponsors as well as to compare these methodologies with those of others' which appear applicable to underwater inspection and monitoring.

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SECTION I

INTRODUCTION

1.1 PURPOSE.

This program evaluates and documents the technology for conducting offshore structural inspections and monitoring by means of nondestructive examination (NDE) techniques. These techniques range from remote sensing systems to instrumentation placed on specified structural members under examination. The results of the program are intended to provide the sponsors insight into the capabilities of the various techniques and to focus their structural monitoring research.

1.2 BACKGROUND.

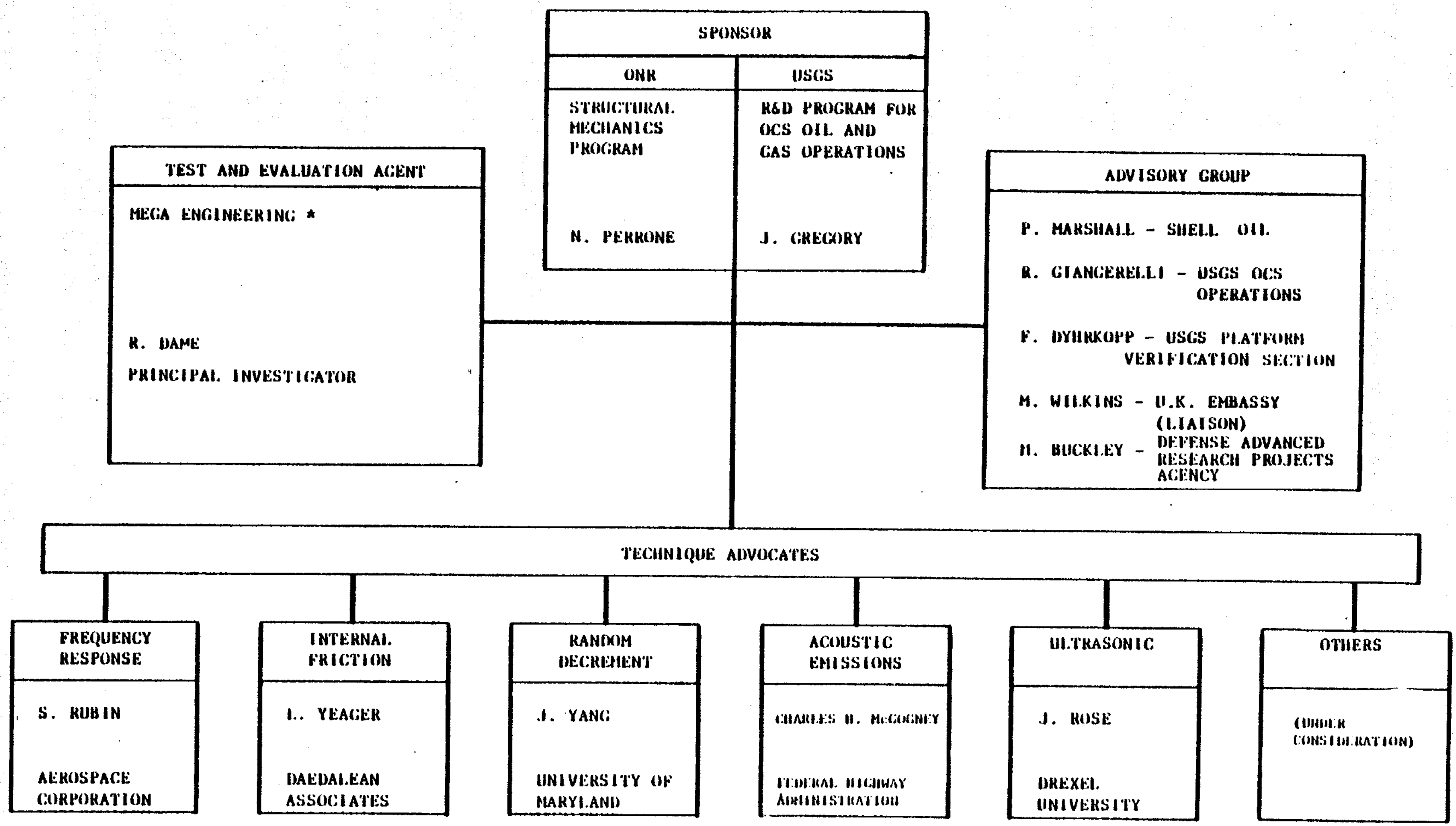
Materials subjected to environmental stress change their vibrational characteristics before giving visual evidence of impending failure. These characteristics range from frequency shift, changes in internal damping, to the development of microscopic cracks, etc. Over the last two decades, and very recently in the offshore structures industry, techniques have been developed to observe and record these material changes for the prediction of structural failure.

There are advocates for each of the techniques. Some of these methods are used operationally with varying degrees of success, depending upon their applications. Some are used as tools for assessing the integrity of such structures as pressure vessels, piping, bridges and even offshore structures.

The sponsors of this program require a comprehensive NDE assessment to support the operational groups in their respective agencies. It is not enough to acknowledge that certain techniques such as frequency response may yield global structural changes or that magnetic particle inspection can identify cracks. Instead, it is necessary to perform exercises which examine the parameters of a structure that are likely to change and to quantify the sensitivity of candidate NDE techniques to detect deterioration while undergoing these changes.

1.3 ORGANIZATION.

The organization for accomplishing the evaluation of NDE techniques for determining offshore structures integrity is shown in Figure 1-1. The program is



* IDENTIFIED FOR TECHNIQUES 1, 2 and 3.

Figure 1-1. NDE Round Robin Organization sponsored jointly by the Office of Naval Research and the U.S. Geological Survey. An advisory Group has been established to offer guidance to the sponsors on the conduct of the evaluations and to provide experienced judgements on their results. Test and Evaluation (T&E) Agents, responsible to the sponsors, will perform all tests, obtaining from the various technique advocates only those instructions deemed essential to carry them out properly.

SECTION II
DESCRIPTION OF NDE TECHNIQUES

2.1 GENERAL.

Candidate NDE approaches include: (a) frequency response, (b) internal friction monitoring, (c) random decrement, (d) acoustic emissions, (e) ultrasonic and possibly others. Considerable research has been accomplished in all of these areas, and they hold promise of eventual viability as important insitu inspection tools for offshore structures.

2.2 FREQUENCY RESPONSE MONITORING

This monitoring concept relies on the identification of natural frequencies and associated mode shape parameters of natural modes of platform vibration. These modal parameters serve as indicators of the presense of underwater structural failure and its location. Diagnosis requires the availability of modal sensitivity results from analyses of a mathematical dynamic model of the platform. Discrimination of failure versus nonfailure causes of modal change is a necessary factor in the success of the method.

There are five variations of concept application, four global and one local:

1. Above Water (Ambient Excitation). The simplest monitoring approach involves the measurement of above water accelerations induced by wind and wave action. Autospectra and frequency response functions are computed between measurements and modal parameters are extracted. This approach is limited to the frequency range free of onboard equipment disturbances. The suitability of modal parameters extracted from ambient vibration has been demonstrated for buildings (References 1 and 2) and, to a limited extent, for a deep-water platform (Reference 3 and 4).

2. Below Water (Ambient Excitation). This augments approach 1 by use of below water accelerometers on the main legs. Instrument placement is possible without divers if the platform is equipped with appropriate chutes (i.e., special pipes for instrument access) down the main legs. Such chutes have been provided during the construction of several existing platforms. An accelerometer package can be lowered into a chute from above water and clamped at any position along the chute.

3. <u>Above Water (Forced Excitation)</u>. This approach uses above water shakers and accelerometers. Shaking should improve the accuracy for determining modal parameters and extend their identification to higher frequencies where equipment noise is present. Modal parameters are determined by measuring the applied forces and determining the acceleration/force frequency responses. Sinusoidal or random forced excitation may be used.

4. <u>Below Water (Forced Excitation)</u>. Approach 3 is augmented with below water accelerometers on the legs.

5. <u>Brace Instrumented</u>. This is a local approach that makes use of underwater accelerometers on jacket brace members. Ambient or forced excitation are applicable. Diver participation is required for field application.

The global approaches (1 to 4) are used for the detection of failures (typically one or more severed members) which result in significant loss of structural strength of a platform. Platforms, which have minimum structural redundancy and are short, provide the greatest sensitivity for detection of failures. Experimental and analytical studies for approach 1 on Shell's SP-62C platform (8 leg, 320 ft water depth; similar to that illustrated in Figure 3-2) show that the approach is promising for this class of platform, if uncertainties due to nonfailure causes are not too large (Project Reports 3 and 4). The frequencies of well identified modes can be detected experimentally to within 0.5 to 1.2% with an assumed allowance for unknown nonfailure effects. Failures are considered detectable if they produce $\geq$ 1% frequency change in a fundamental lateral or torsional mode, or $\geq$ 2% change in certain clearly identified higher modes. It has been shown analytically that single vertical diagonal member failures (e.g. members in a vertical plane) typically produce $\geq$ 1% frequency change in a fundamental mode. The load redistribution, due to failures yielding a lesser change, produces a maximum load increase of 19%. According to Reference 5, this level of sensitivity can be useful for Gulf of Mexico platforms since no more than 40% of design loading will occur when the platform is manned and operating. Higher loadings occur during hurricanes, but the platforms are evacuated and wells shut in. Global approaches 2 to 4 show promise for increased sensitivity to failure and improved discrimination from nonfailure changes.

Approach 5, brace instrumentation, is most applicable for identifying the presence of severe cracking or severance within a particular framing section or a particular member, depending on the framing geometry. If a leak occurs in a member which does not present a structural strength problem, it will nevertheless interfere with detection of cracking in members which are of concern and may produce false indications of failure.

2.3 INTERNAL FRICTION MONITORING.

The internal friction monitoring method is based upon an understanding of the behavior which metals manifest when subjected to stress. This behavior is a deviation from perfect elasticity and causes energy dissipation within a metal which is related to its granular structure. It has been known for more than a century that metals do not exhibit perfect elastic behavior even at very low levels of stress. Because of this "anelasticity," part of the mechanical energy input to a metal is converted to heat, and the various mechanisms by which this process occurs are collectively termed internal damping. Increases in internal damping during the service life of a metal indicate progressive fatigue from which the remaining structural life can be determined.

Internal damping may be measured by subjecting a structure to a low-stress wave and recording the decrement. A simple beam can be excited by merely plucking it, or a complex structure can be driven by means of a vibration shaker. The decay response of the beam may only contain the fundamental frequency and its overtones, but complex structures will exhibit many decaying responses masked within a single envelope.

In a complex structure, once degradation is detected, the crack must be located. For a structure of welded columns, beams, braces, and so on, accelerometers can be placed at various locations, and by collectively analyzing their responses, structural deterioration or failure may be identified. Instruments can also be limited to key locations, as for example, where fatigue deterioration is most probable. Still unanswered, however, is the applicability of the technique to large structures, such as offshore platforms, which are subjected to complex fatique regimes resulting from wind, wave, corrosion, ocean floor erosion, and changing deck loadings.

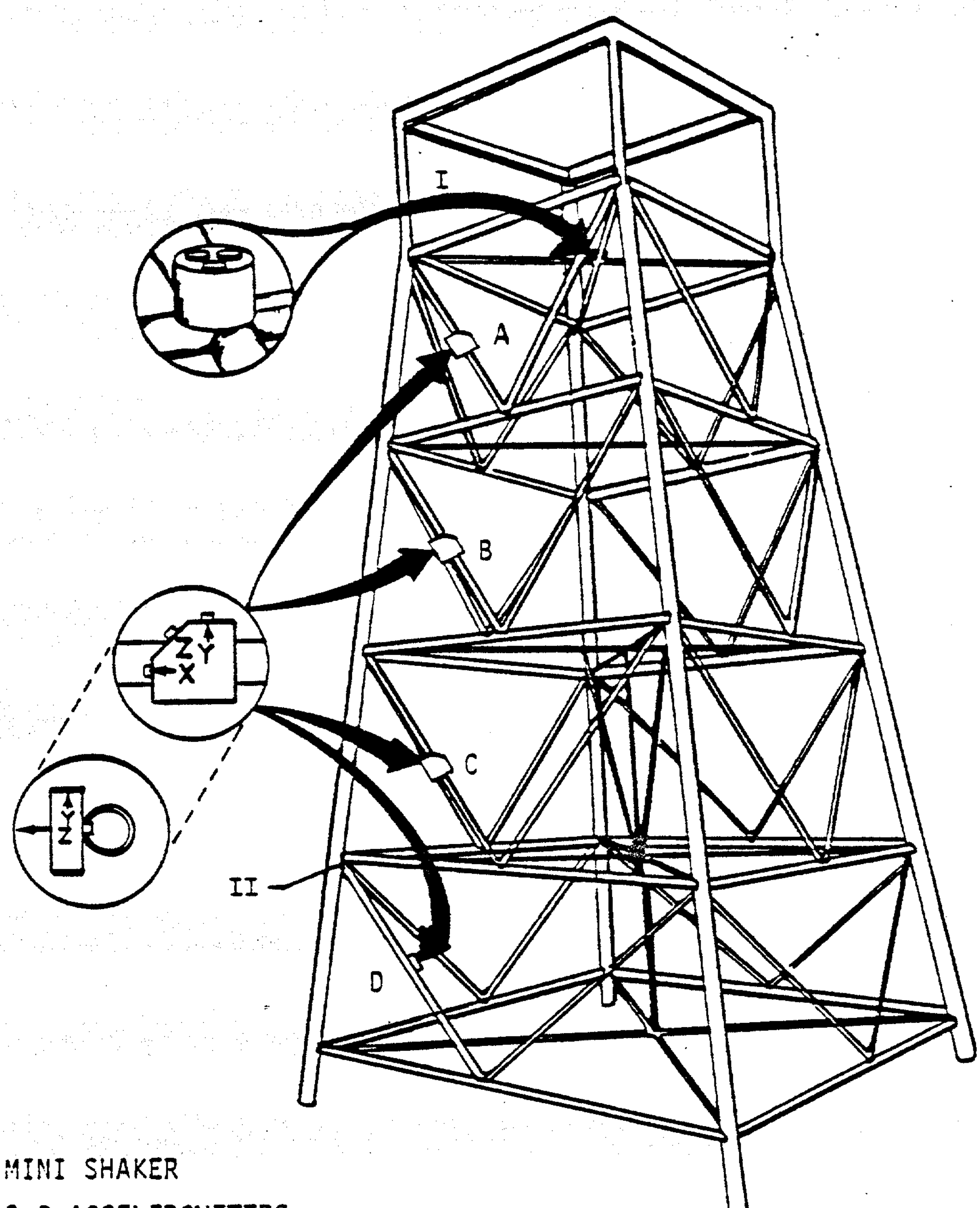
Over the past year, the internal friction monitoring technique has been applied to a 16-foot-high, 1:14-scale model offshore platform (Figure 2-1). In the model, a source transducer is located above the water level (point I) in order to simulate in-service conditions. Vibrational energy is pulsed down the legs and across the braces where accelerometers are positioned to record changes in pulse decay characteristics.

As illustrated in the figure for the particular model used, failed joints are located by means of single three-axis accelerometers placed on a diagonal brace of each bay. Using spectral analysis, baseline information is obtained on the various resonances detected by all accelerometers. These have indicated that all accelerometers are sensitive enough to detect resonance changes which, in turn, indicate increases in internal damping, that is, damping capacity.

The efficiency of detecting cracks or severed members depends upon knowledge of structural dynamics, data processing skills, and experience with the technique on complex structures. For purposes of illustrating the technique on the model, the following example is used.

A wide band signal of 1-20 kHz, synthesized by a synchronous function generator, is transmitted down the structure. Three axis accelerometers at locations A, B, C and D are exicted and their responses are recorded and analyzed. For each accelerometer, the two highest peaks in the frequency spectra, for the x, y, and z axes, are noted. From experience with the model, these highest peaks are often found to be 30-50 dB above most of the others. Since it has been determined that much vibrational energy exists at these frequencies, their behavior is monitored so as to detect progressive failure.

After these baseline data are obtained, the structure is fatigued by means of the hydraulic loading device in increments of above 5,000 cycles, whereupon the logarithmic decrements are measured at all the high energy peaks mentioned above. These peaks are examined by exciting them sequentially at their frequencies by use of the acoustic driver, I. The Data, $\Delta W/W$, (the specific damping capacity), which is the ratio of energy dissipated to input energy, is



I - MINI SHAKER
A,B,C,D 3-D ACCELEROMETERS
II - FAILURE POINT

Figure 2-1. 1/14 Scale Model Offshore Platform statistically analyzed, and after about 20 data points, confidence bands are established. If Δ W/W exceeds the upper band by three times the standard deviation, cracking is inferred; and after further monitoring the behavior of the selected spectral peaks, a completely severed joint can be determined.

To locate the positions of the cracking or breaking members, experience and skill are necessary. In the example of the model, the responses of the accelerometers nearest to a crack will first exceed the upper confidence band and, as the crack grows, more of the accelerometers responses will exceed their limits.

Figure 2-2 illustrates damping capacity measurements obtained during a fatigue test in which failure occurred at point II (Figure 2-1). Accelerometers C and D (immediately above and below the failure) indicated the crack on one axis and for one of the two resonances selected for analysis. For example, in insert 4 on Figure 2-2, CY (accelerometer C, Y axis) shows a dramatic change in Δ W/W for the 4210 Hz resonance though not for the 813 Hz peak. When the joint breaks, all accelerometers, on all axes, respond with assurance, even those located more than a bay away (insets 1, 2, and 3 of Figure 2-2).

2.4 RANDOM DECREMENT.

The random decrement (RANDOMDEC) technique is a general method of analysis which is particularly well suited to the class of problems in which characteristics are desired of an in-service structure subjected to unknown random excitation. Only the measurement of the dynamic response of a structure, not the excitation, is required for the analysis. On offshore platforms, such inputs mostly result from ambient conditions, such as waves and wind.

The analysis of a time history of the response at some location on a structure produces a unique response signature which is dependent on structural properties such as natural frequencies and damping. Having a response signature, which is sensitive to changes in structural properties, allows changes to be detected.

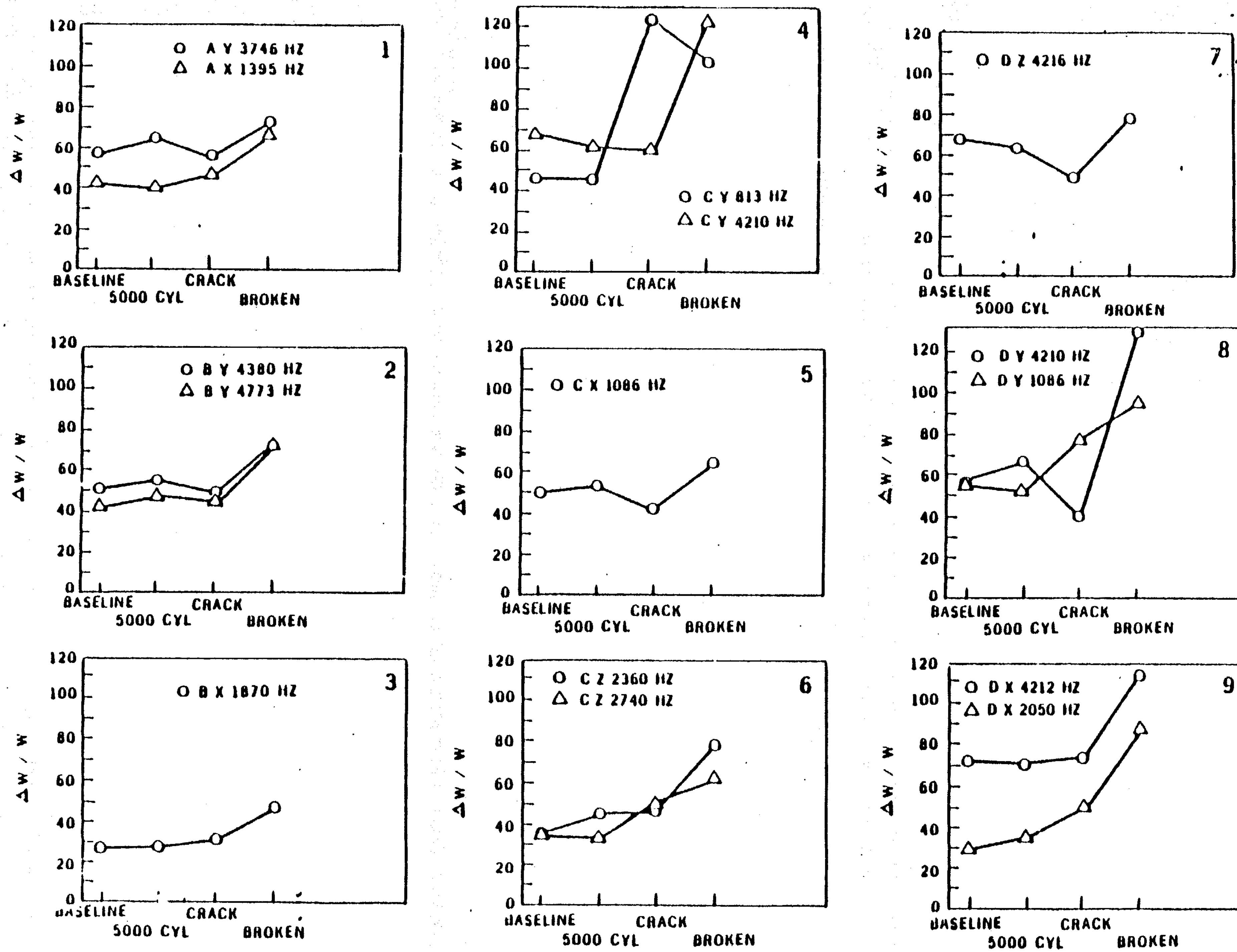


Figure 2-2. Test Results of 1/14 Scale Model Platform

The RANDOMDEC method analyzes the measured output of a system subjected to some ambient random input. After analysis, a signal results which is the free vibration response or response signature of the structure. The ability to obtain a unique response signature common to many different modes (usually accomplished by filtering the output) enables detection of early damage before overall structural integrity is affected. Local flaws, such as cracks that are too small to affect overall integrity, could have a significant effect on the signatures of the higher modes. Figure 2-3 illustrates the acquisition of a RANDOMDEC signature.

Cracks can show up as small blips in the "hashy" high modal density region of the response spectral density, and as they grow, the failure mode frequencies decrease and approach the fundamentals where failure becomes imminent. Flaws must be detected early enough--that is, at high enough frequencies--if corrective action needs to be taken. Detection is accomplished by passing a random signal through a bandpass filter which is set to screen high frequencies. If a failure develops, the signature will be affected dramatically because it will dynamically couple with structural modes within these bandpass frequencies.

The RANDOMDEC technique is applied to the filtered response data of the vibrating structure both numerically and on a special analog computer. From these signatures, the sensitivity to fatigue cracks of various lengths can be shown.

A 1:13.8-scale model offshore platform has been constructed (Figure 2-4). Its design was based on a dynamic similitude study, (Reference 6). The model platform was fatigue loaded hydraulically and a systematic study of the effect of structural damage was conducted. Responses at various positions along the structure, subjected to random input, were obtained at various intervals of cyclic loading. Fatigue cracks of varying lengths were measured at the welded sections. Response-time histories were recorded and analyzed to obtain random decrement signatures, and from these recordings their sensitivity to the fatigue cracks of various lengths were correlated.

Finite element modeling and analysis of the offshore platform, using the NASTRAN computer program, were performed to determine structural natural frequencies, mode shapes, and transient responses for purposes of instrumentation

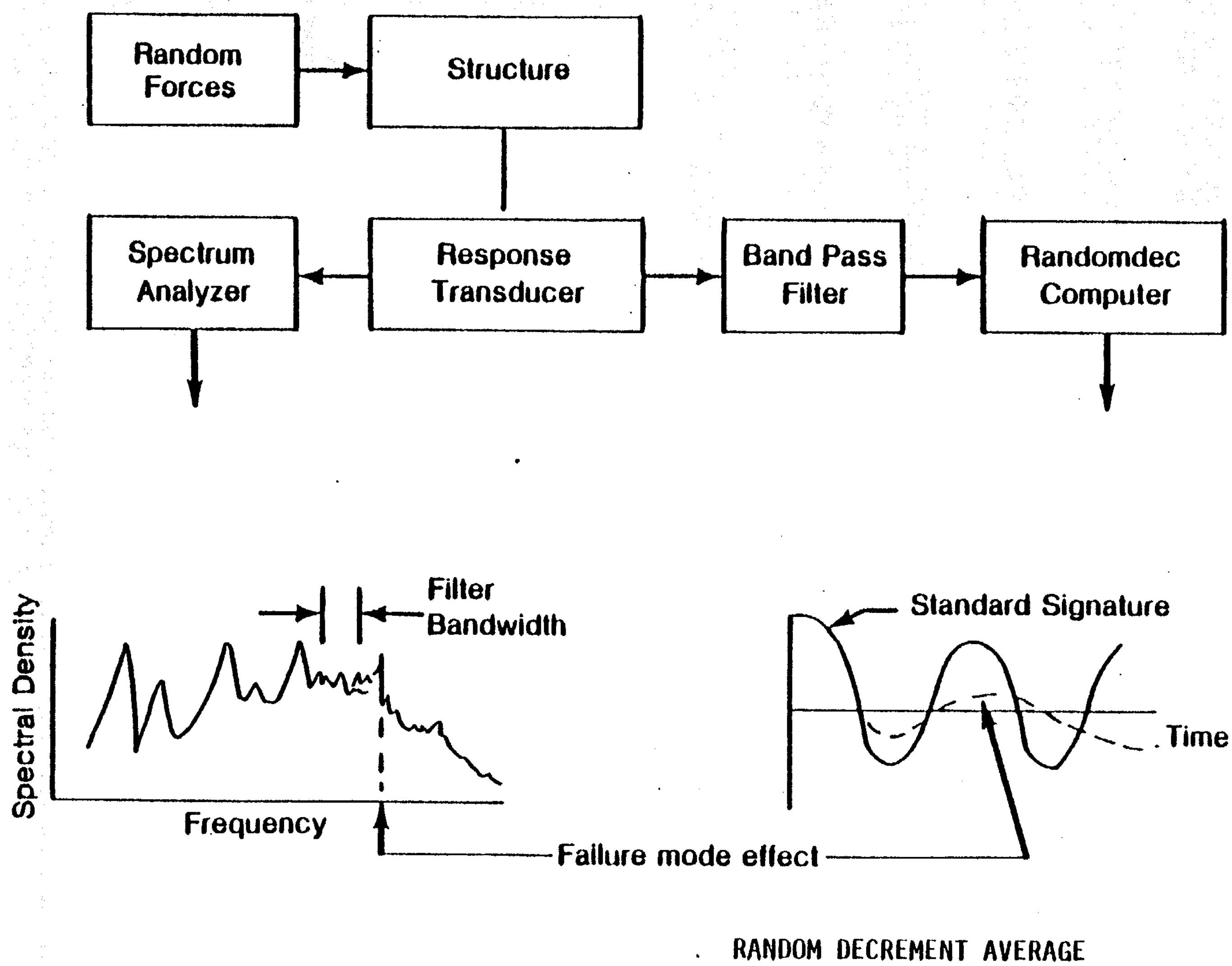


Figure 2-3. Acquisition of a Random Decrement Signature

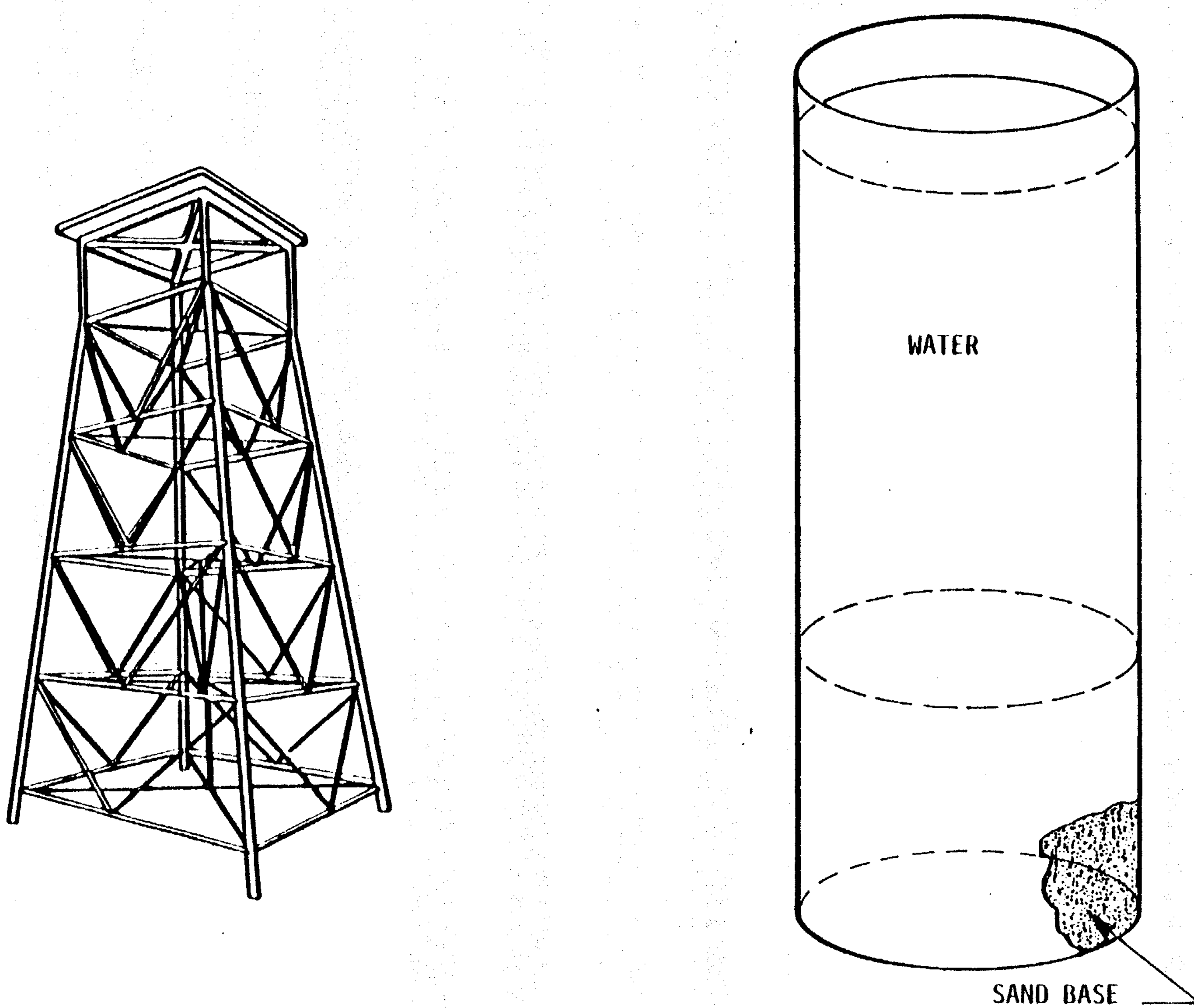


Figure 2-4. Platform Model With Water Tank

selection, scaling verification, and dynamic behavior of the structure. Homogenized finite element beam models were developed for the full-scale and the 1:13.8-scale model. The models yield gross structural frequencies, mode shapes, and transient responses which provide a verification of the scaling.

Finite element space frame models, Figure 2-5, were developed to obtain detailed dynamic stress states, structural frequencies, and mode shapes. This aided the assessment of probable locations of cracks and the estimation of fatigue life. Effects of simulated structural damage on natural frequency and mode shapes were studied. Results demonstrated the ability of the random decrement technique to measure progressive failure on the models in air. The model structure is to be tested in water and on a soil foundation.

2.5 ACOUSTIC EMISSIONS.

Acoustic Emission is a phenomena whereby transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material. Acoustic emission testing requires that an energy reservoir (i.e., strain energy) must be present. A propagating flaw in a structure then transduces minute amounts of strain energy to a transient elastic wave which propagates at the speed of sound in the structure. The spectral content of this signal is very broad and can be detected up to frequencies as high as 30 MHz. Most practical applications involve monitoring frequencies from 30 kHz to 1 MHz.

Acoustic emission monitoring experiments have successfully demonstrated the ability of the technique to detect crack initiation and crack growth at very early stages in laboratory simulations of the fatigue of typical offshore structural joints. This testing has been undertaken at various laboratories in the UK and at private laboratories in the U.S. Additional programs are underway to determine the viability of the technique to detect cracking in the marine environment.

Acoustic emission monitoring will fulfill several different roles in a structural integrity program for steel jacket structures:

a. Provide a statistical indication of overall platform integrity by monitoring selected nodes to detect crack initiation.

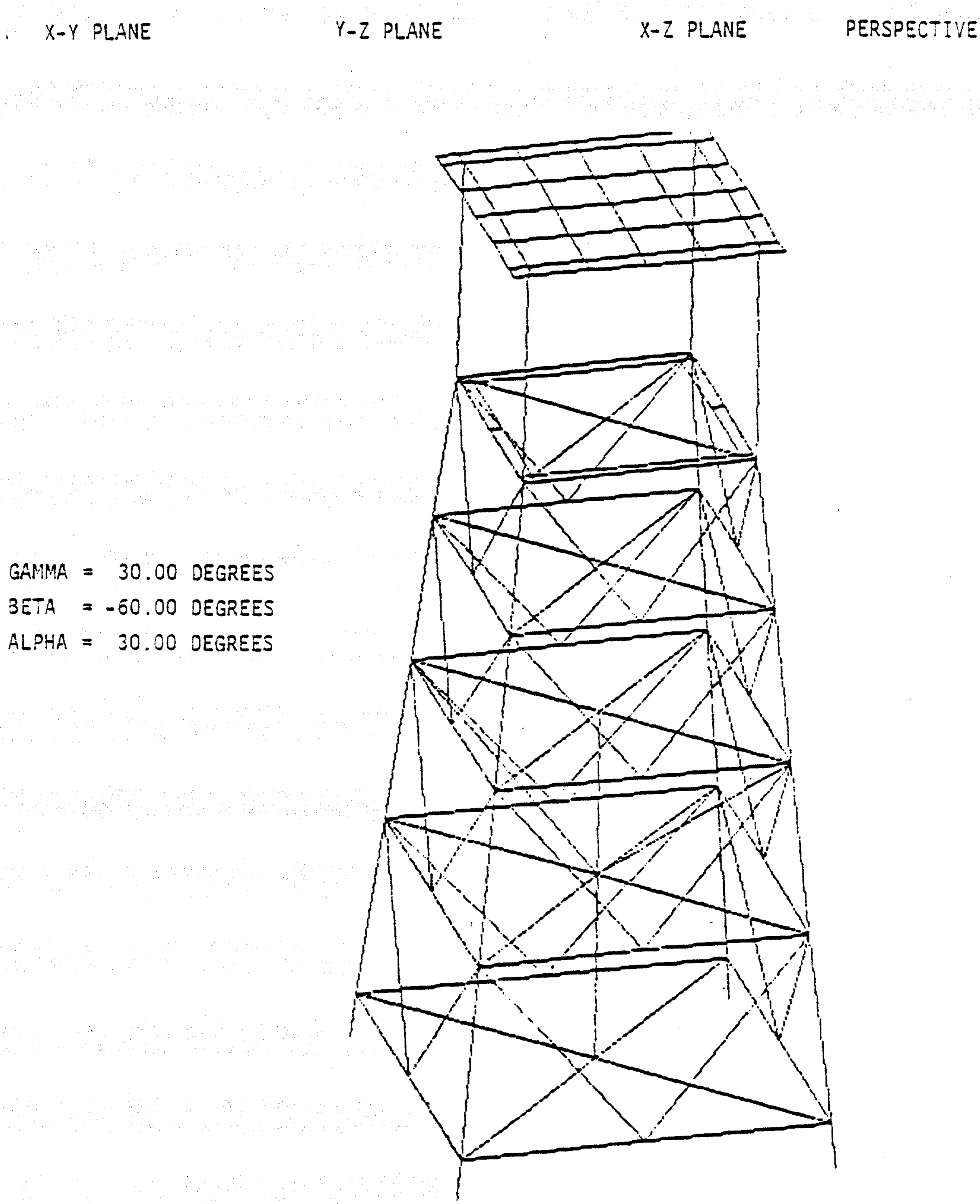


Figure 2-5. Offshore Platform Model (NASTRAN)

b. Conduct nodal monitoring to assess the integrity of all major nodes. With this approach, the system would be further expanded by the addition of transducers to monitor crack growth once detected at a specific node.

c. Monitor relatively long members, using few transducers, where the acoustic transmission path would encompass multiple nodes. This approach lends itself particularly well to platforms with flooded legs or "tension leg" platforms.

The applicability of these approaches depends upon factors of design, environment, water depth, and etc., and may be supplemented by other techniques such as diver or submersible inspection.

The potential advantages and disadvantages of acoustic emission monitoring is summarized as follows:

a. Advantages:

(1) Early crack detection, perhaps even to the level of crack initiation.

(2) Ability to monitor progressive deterioration.

(3) Ability to locate cracked area and the specific cracked member.

b. Disadvantages:

(1) Lack of existing standards to quantify deterioration.

(2) Difficulty in interpreting results.

(3) Expense of initial installation.

(4) Potential false alarms until sources of extraneous noise are identified.

(5) Potential need to replace transducer/cable which may have failed as a result of hostile environment.

Technology development in an acoustic emission program of study for the Federal Highway Administration may be applicable to offshore structure monitoring systems. The Federal Highway Administration program, carried out by Battelle Northwest, developed the following prototype acoustic emission test system.

The system has a digital memory acoustic emission (AE) monitor with source isolation to limit accepted data to emissions originating from a predetermined area. The system includes a monitor unit (amplifiers, source isolation circuits, digital memories, and memory programming controls) in a compact 3 1/4 x 7 x 9 inch (82.6 mm x 177.8 mm x 228.6 mm) housing weighing 5 pounds (2.27 Kg.) A separate power supply provides power from either a 100 volt-60 hertz connection or from internal rechargeable batteries. Three low power tuned preamplifiers and three AE sensors complete the measurement system. Accessory to this is a visual memory readout instrument.

A digital memory AE monitor system has been field tested on two in-service steel highway bridges and on box girder fabrication welds at a steel plant. Testing has indicated that the unit performs as intended, is relatively fast to set up, and can function in high background noise and still detect flaw growth.

2.6 ULTRASONIC INSPECTION TECHNIQUE.

A dual element transducer technique for characterizing defects in offshore structural components will be evaluated. The first work task will be to design a suitable transducer configuration for transmitting ultrasonic waves completely around the tubular offshore components. Design variables of the transducer configuration include roof angle of transmitter and of receiver, transducer size, wedge shape and material selection, separation distance between elements, and suitable wedge angle for a complete inspection of the tubular element, transducer center frequency probably around 100 kHz, permanent contact design, and the possibility of including a second dual element probe on the far side of the pipe section for improved sensitivity. A number of other design variables may also be considered. Many of these transducer systems might actually be included near critical areas of an offshore structure. Provisions may also be explored for examining reflectors near the welded areas of the structure. The technology for inspecting small tubular elements is well developed and it is hoped to extend this technology to larger offshore structural components.

A global inspection procedure similar to that outlined above is being developed that allows ultrasonic waves to travel completely around a K-joint. A matched filter signal processing technique is also being developed that looks for a change in the ultrasonic signal that can be correlated with some kind of damage at a particular location in the K-joint.

Data collection will be as follows. Information from 12 different locations will be acquired. The signals will be acquired five times at each transducer location for a total of 60 signals. Every signal will be stored in a storage device for further signal processing.

The procedure for detecting changes in the vicinity of a K-joint will be approached by a correlation analysis or by a matched filter technique. The underlying philosophy is basically template matching. This requires the generation of a library of signals obtained from a collection of K-joints. This K-joint reference library can be generated on site at the actual test location. During the initial inspection of the structure, signals from the K-joint are stored. Once the signals are stored, a variety of methods are available for comparison, on a correlation basis, with signals obtained at a later inspection. A radical change in the characteristics of a signal from a particular joint would indicate the necessity for closer investigation of the particular joint. Minimum distance classification and matched filtering are two well understood methods for detection of signal changes. Threshold values on the signal changes must be acquired through an adaptive learning process for a variety of damage situations.

2.7 OTHER TECHNIQUES.

Other techniques are being considered as prospective candidates for evaluation in the program. These techniques are magnetic particle inspection, visual and acoustic imaging, fiber optics, etc.

SECTION III
EVALUATION PROCEDURES

3.1 PROGRAM GOALS.

The main goal of this program is to evaluate techniques that might merit further development for the examination of offshore structures. Secondary goals include: (a) the discrimination between failure and non-failure, (b) discrimination of the degree of damage, and (c) determination of the location of the damage. For each of the different techniques to be evaluated and compared, the development status of each will be related to a common baseline. This will provide a valid basis for the comparisons.

3.2 TEST APPROACH.

It is planned to use scale models, a four leg platform and an eight leg platform for global structural evaluations, and a "K" joint for local evaluation of member joints. The intent is to evaluate the models in a way which will be meaningful to actual offshore operations. Non-failure changes, for example, may include simulated marine growth, a change in deck mass, or a change in the base support. Failure type changes could include severed members, or joint cracking.

Test and Evaluation (T&E) Agents will execute all tests on the four and eight leg structures and Technique Advocates will evaluate the test data. Since the purpose of the evaluation is to assess the utility of each concept for failure identification, the evaluators will be "blind" to actual test changes (i.e., they will not have knowledge of failure or non-failure changes in the models).

3.3 TEST CONFIGURATIONS.

Three models will be used for the testing. The models are being fabricated by the University of Maryland, Physics Department shop.

3.3.1 FOUR LEG PLATFORM. The four legged model platform, Figure 3-1, is similar in design and construction to that used by the University of Maryland (Random Decrement technique) model (scaled 1:13.8) and similar in configuration to the Daedalen Associates (Internal Friction technique) model (scaled 1:14). Both models

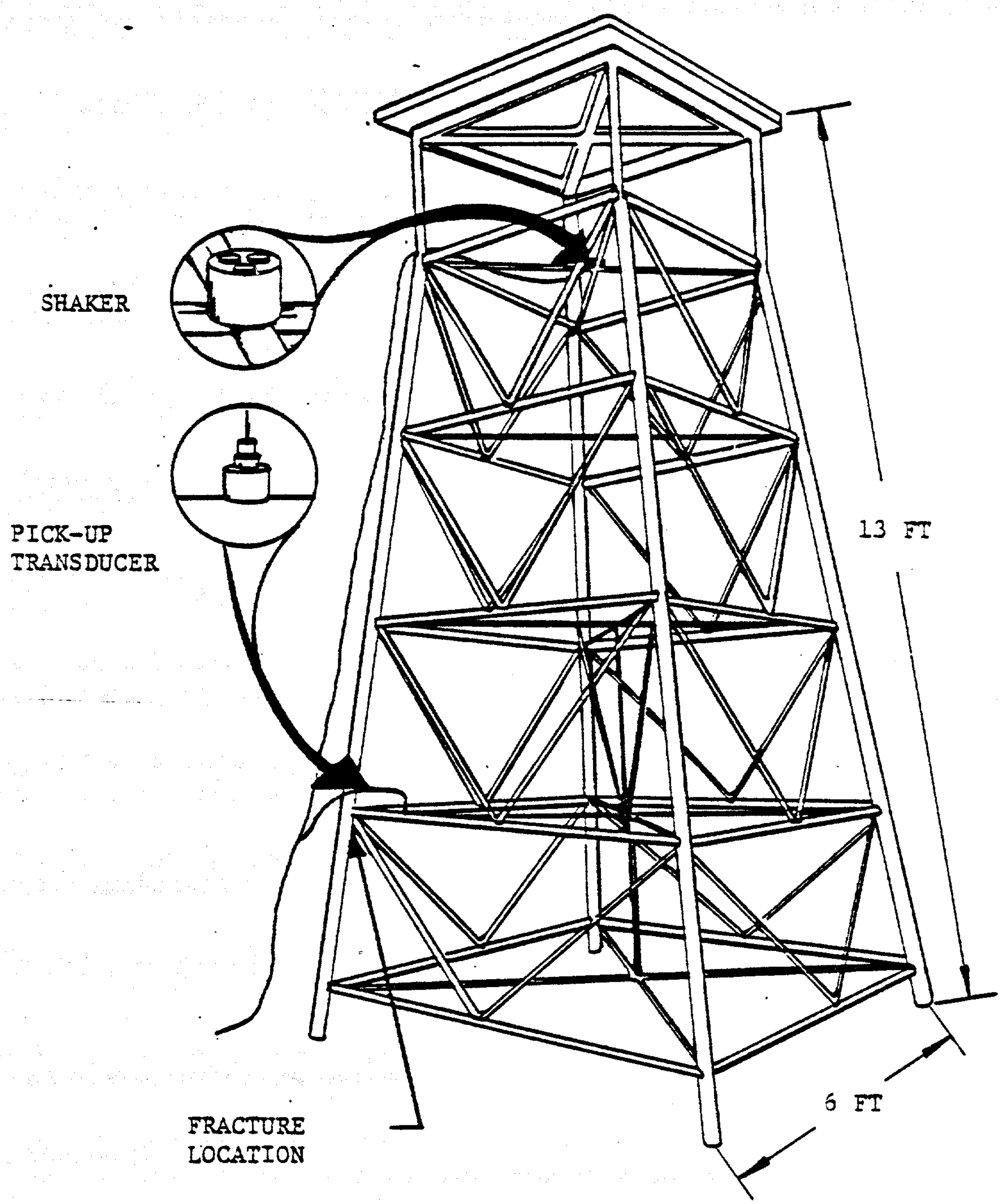


Figure 3-1. Scale Model of Offshore Platform

were scaled from actual prints of Platform B, Block 48, South Marsh Island, Gulf Oil Corporation. The platform is located in 105 feet of water and was erected in 1965. Because the University of Maryland model resulted from a similitude analysis, it is selected for use.

3.3.2 EIGHT LEG PLATFORM. The second model (Figure 3-2) is of a typical 8 legged Gulf of Mexico template platform. It is a Shell Oil Company self-contained drilling platform, South Pass Block 62A, located in 320 feet of water. Model fabrication is to be delayed until scaling analyses are accomplished.

3.3.3 K JOINT. A "K" joint model for local evaluation of member joints will be fabricated. It is a typical joint configuration from the eight leg platform model. The scaling has been increased to eliminate potential scaling problems for comparison with actual field conditions. A sketch is shown in Figure 3-3.

3.4 TEST PROCEDURES.

The test procedures for each technique will be developed by each of the Technique Advocates. The procedures must address the failure and non-failure damage scenarios that are presented below. The test procedures will be in sufficient detail to describe the characteristics and locations of sensors, special testing instructions and type of data to be recorded.

3.5 FAILURE AND NON-FAILURE DAMAGE SCENARIOS.

Three types of scenarios are used: major damage, minor damage or non-failure change, and changed environment.

3.5.1 MAJOR DAMAGE SCENARIO.

- Condition #1 - Severed diagonal brace on one face at mid-level
- Condition #2 - Two severed diagonals at mid-level, one on each of opposite faces
- Condition #3 - Severed horizontal at base
- Condition #4 - Two severed horizontals at base, one on each of opposite faces
- Condition #5 - Changed foundation condition. Change from legs fixed to the floor to legs setting in sand

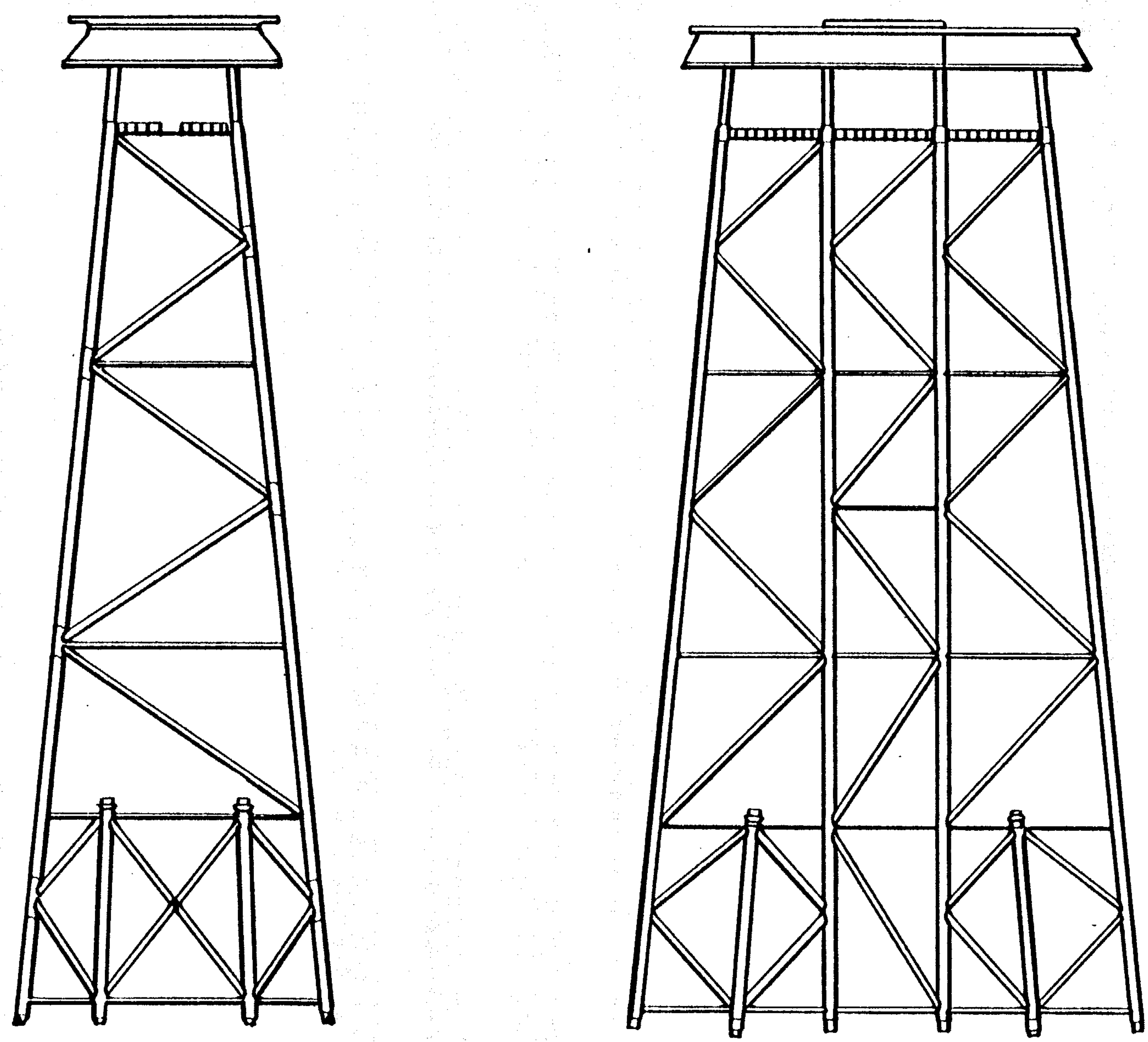
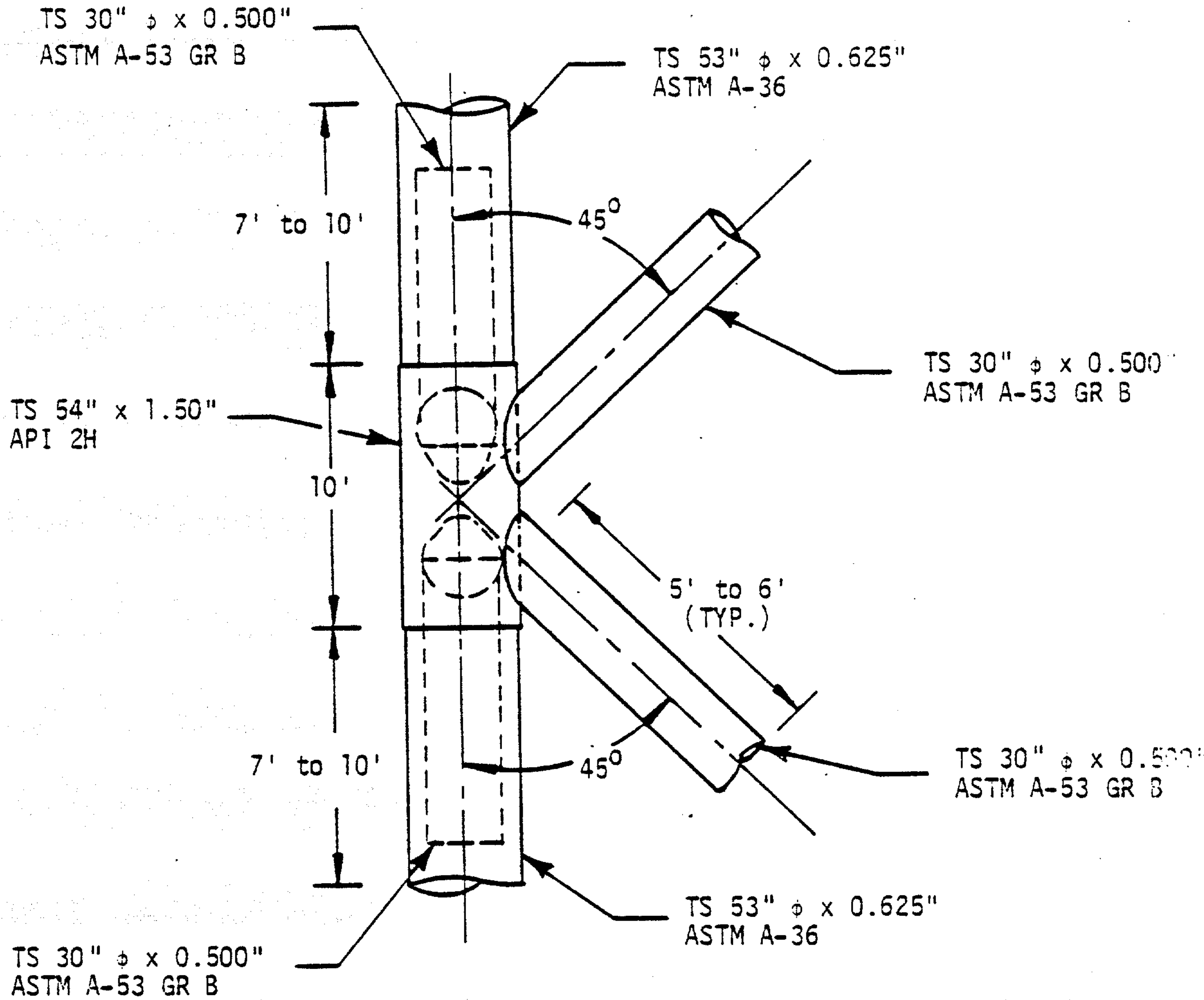


Figure 3-2. Gulf of Mexico Type 8-Legged Platform



MEMBER	QUANTITY	SIZE FULL SCALE	SIZE 40% SCALE
JOINT CAN	1	TS 54" ϕ x 1.50" API 2H	TS 21" ϕ x 0.625" ASTM A500 GR B
LEG	2	TS 53" ϕ x 0.625" ASTM A-36	TS 21" ϕ x 0.25" ASTM A-36 or A-53 GR B
DIAGONAL	4	TS 30" x 0.500" ASTM A-53 GR B	TS 12" ϕ x 0.25" ASTM A-36 or A-53 GR B

Figure 3-3. "K" Joint Model

3.5.2 MINOR DAMAGE OR CHANGE.

Condition #6 - Bent diagonal members in upper bay
Condition #7 - Change in deck mass
Condition #8 - Simulated marine growth
Condition #9 - Crack in one or two horizontal members
Condition #10 - Progressive cracking of horizontal and diagonal members
Condition #11 - Installation of one or two riser pipes

3.5.3 CHANGED ENVIRONMENT - PLATFORM IN WATER. Reexamine techniques with platform immersed in water. Select conditions from paragraphs 3.5.1 and 3.5.2.

3.6 EVALUATION CRITERIA.

The criteria to be used in the evaluation of each technique is based on the program goals presented previously in this section. Each technique will be evaluated for its ability to:

a. determine if deterioration occurred during the test,
b. the type of deterioration,
c. the degree of deterioration, and
d. the location of the damage.

3.7 MECHANICS OF REPORTING THE EVALUATIONS.

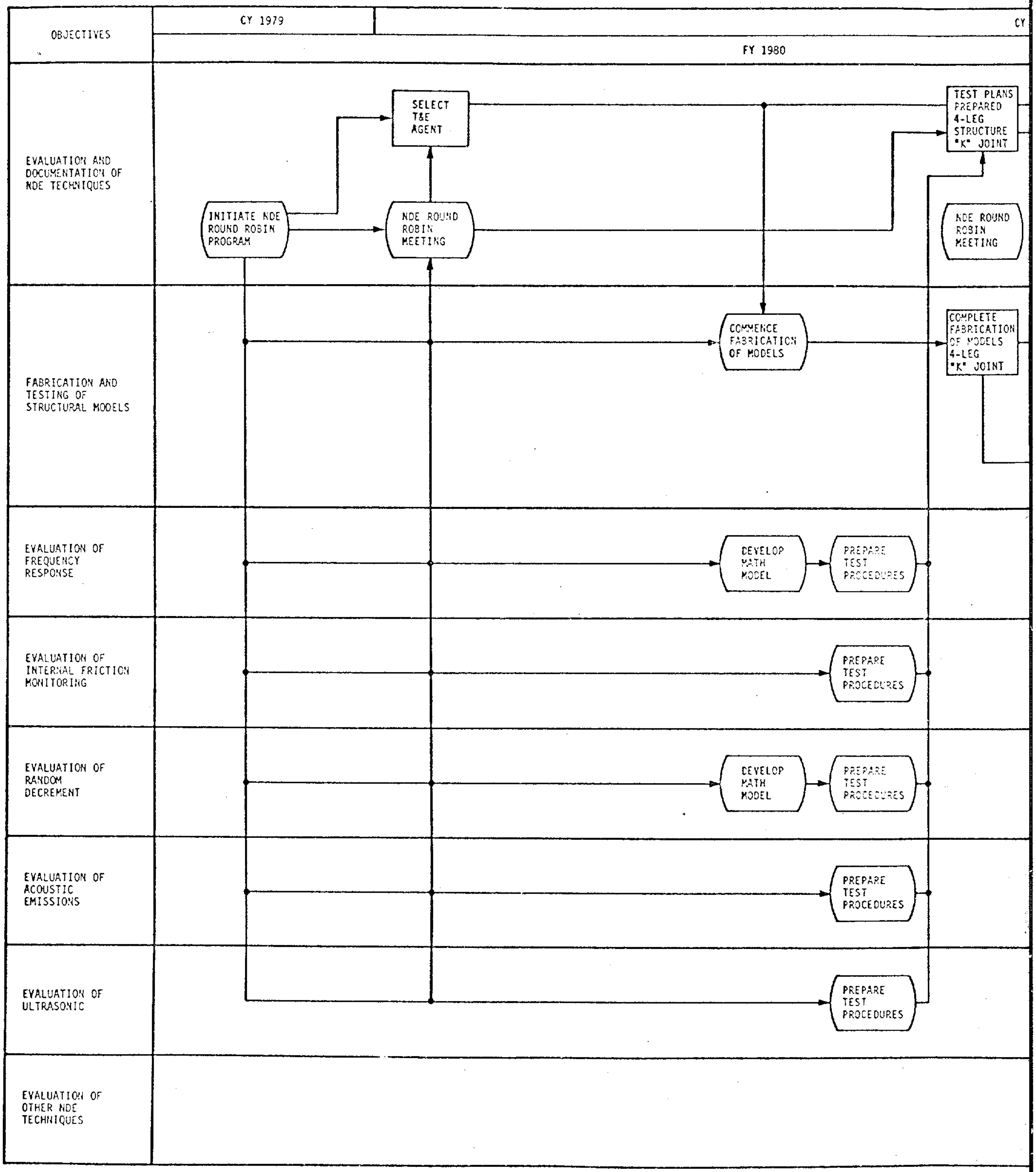
Advocates will obtain test data from the T&E Agent and will report to him the resulting findings, together with the rationale used in the determination. Checklists will be developed for use in reporting the test results. A standard format will be used for all techniques. The T&E Agent will compile the completed checklists and develop a matrix to illustrate comparative results.

SECTION IV
MILESTONES

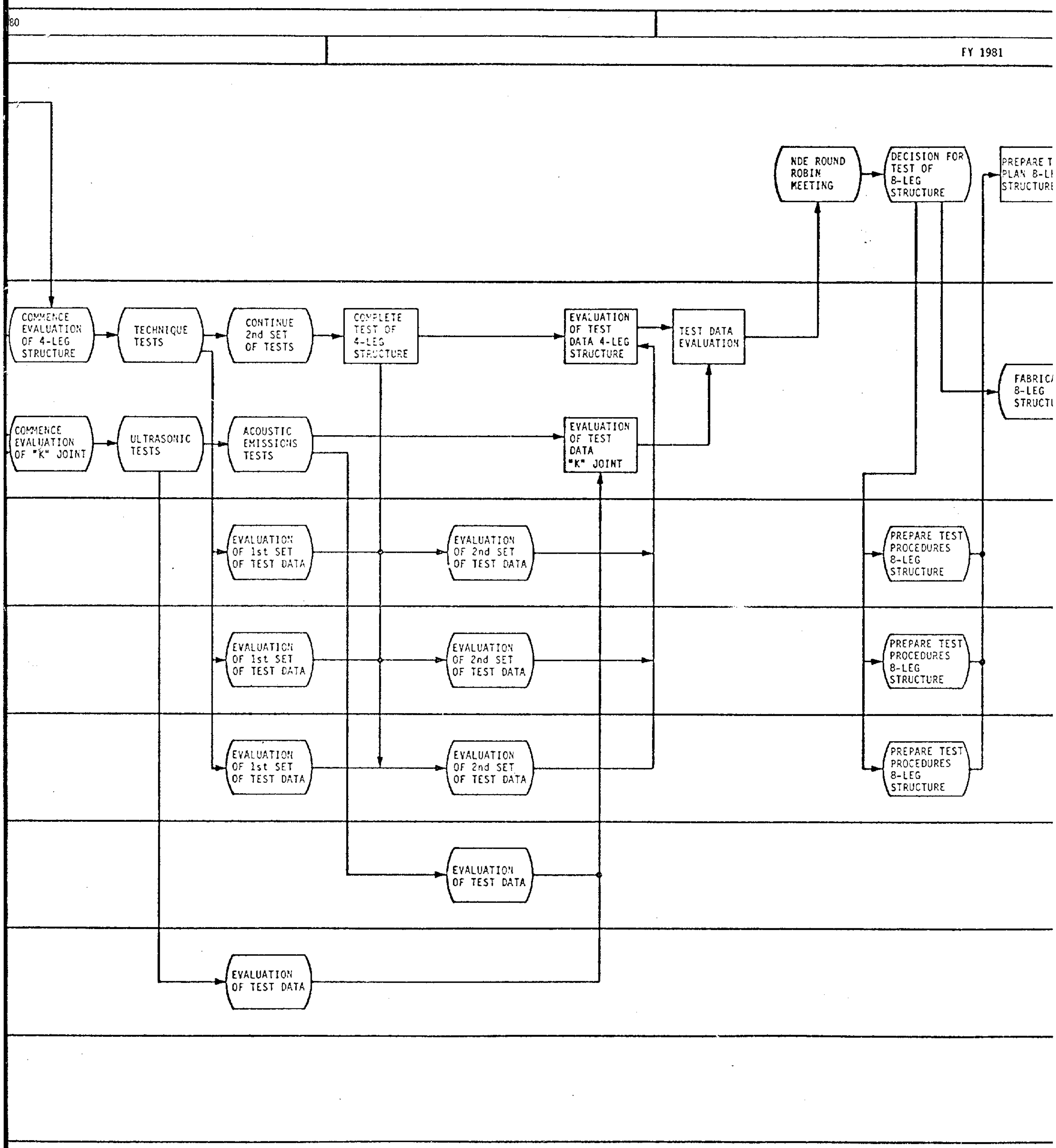
4.1 GENERAL.

The NDE Round Robin Milestone/Event Interdependency Network is shown in Figure 4-1. This details the actions and time schedule for each of the major areas of the program.

NDE ROUN


OBJECTIVES
CY 1979
CY
FY 1980
EVALUATION AND DOCUMENTATION OF NDE TECHNIQUES
FABRICATION AND TESTING OF STRUCTURAL MODELS
EVALUATION OF FREQUENCY RESPONSE
EVALUATION OF INTERNAL FRICTION MONITORING
EVALUATION OF RANDOM DECREMENT
EVALUATION OF ACOUSTIC EMISSIONS
EVALUATION OF ULTRASONIC
EVALUATION OF OTHER NDE TECHNIQUES
SELECT T&E AGENT
INITIATE NDE ROUND ROBIN PROGRAM
NDE ROUND ROBIN MEETING
TEST PLANS PREPARED 4-LEG STRUCTURE "K" JOINT
NDE ROUND ROBIN MEETING
COMMENCE FABRICATION OF MODELS
COMPLETE FABRICATION OF MODELS 4-LEG "K" JOINT
DEVELOP MATH MODEL
PREPARE TEST PROCEDURES
PREPARE TEST PROCEDURES
DEVELOP MATH MODEL
PREPARE TEST PROCEDURES
PREPARE TEST PROCEDURES
PREPARE TEST PROCEDURES

D ROBIN PROGRAM EVENT/MILESTONE INTERDEPENDENCY NETWC



RK

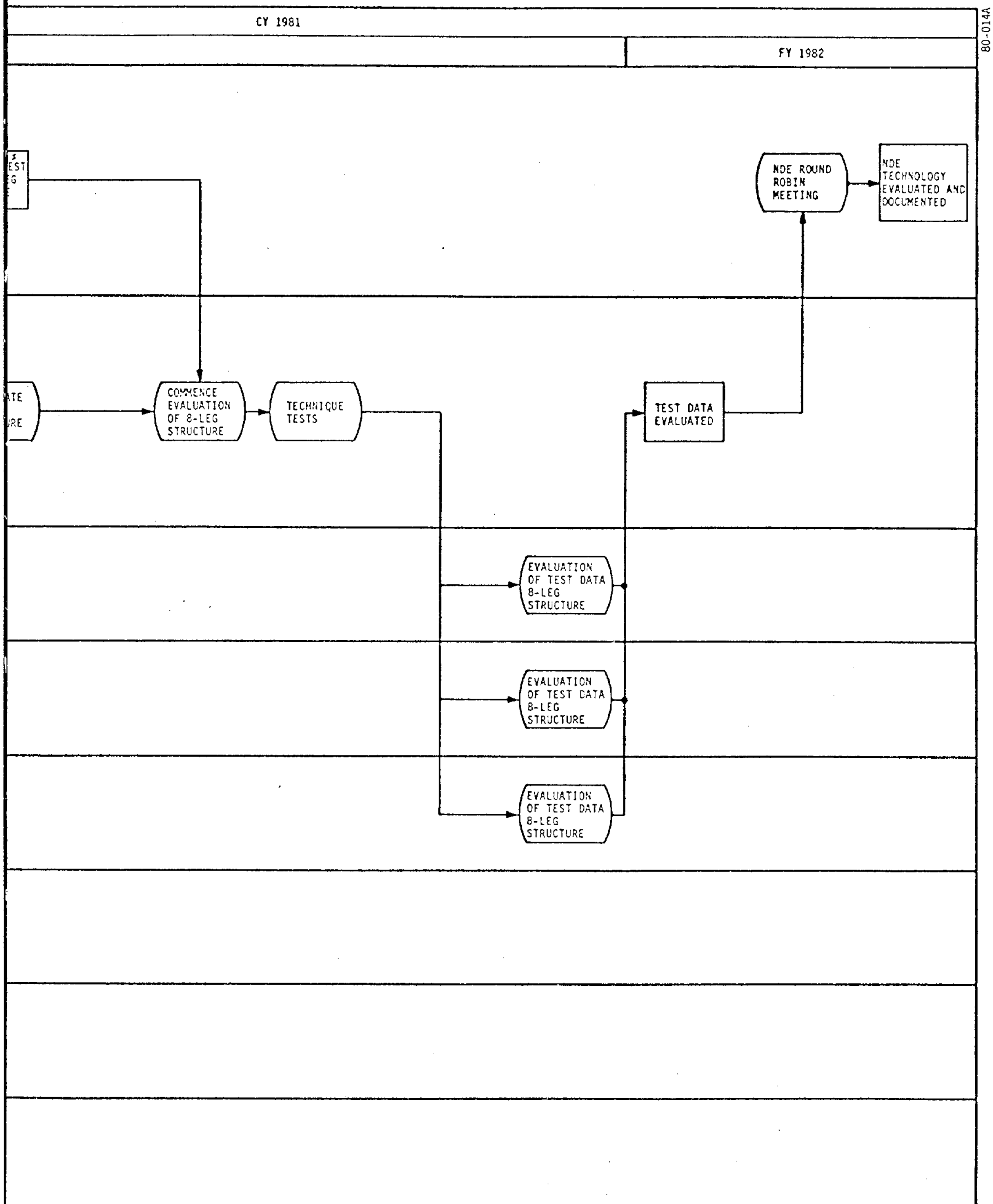


Figure 4-1. NDE Round Robin Program Event/Milestone Interdependency Network

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3. Rubin, S., Ambient Vibration Survey of an Offshore Platform, accepted for publication by ASCE Journal of the Engineering Mechanics Division (also presented at the ASCE Spring Convention and Exhibit, Boston, 2-6 April 1979).

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PROJECT REPORTS

1. Li, C.S., Yang, J.C.S., Dagalkis, N., 1979, Dynamic Analysis of Prototype and 1:13.8 Scale Model of an Offshore Platform: ONR-USGS Report No. NO-78-C-0642-3.

2. Miller, M.W., Spiegelthal, D., Yang, J.C.S., Dagalkis, N., 1979, Application of the Random Decrement Technique for Detection of Structural Cracks: ONR-USGS Report No. NO-78-C-0632-4.

3. Instrumentation of Fixed OCS Platforms, Aerospace Corporation, El Segundo, California, October 1977.

4. Rubin, S., Coppolino, R., OCS Instrumentation Monitoring Evaluation, Aerospace Corporation, El Segundo, California, June 1979.

APPENDIX B

DAMAGE EVALUATION FORMS

THE AEROSPACE CORPORATION

Post Office Box 92957, Los Angeles, California 90009, Telephone: (213) 648-5000

22 May 1981

Dr. Richard Dame
Mega Engineering
11961 Tech Road
Silver Springs, Maryland 20904

Subject: Assessments of First Four Damage Scenarios

Dear Dr. Dame:

Enclosed are our completed response forms for the four damage scenarios of test series 1. See the attached figure (from our test plan) for accelerometer designations, axes, and labeling of regions on the tower. Underwater brace accelerometers (21-27) were not considered for the evaluations.

Possibilities for failure were considered within the context of the damage scenarios identified in the draft program plan, dated April 1980, section 3.5. For example, leg severances were not considered, other than the possibility of a leg bottom failure that might represent an extreme foundation change (condition #5). Also, the presence of multiple horizontal failures involving more than a single level was not considered as a possibility. On the other hand, going beyond the plan, the possibility of diagonal failures was not limited to the mid-level of the tower (conditions #1 and #2).

We hope that, in the near future, we will be informed of the degree of success in our assessments. We look forward to participation in a meeting to discuss the various results in more detail and to explore the possibilities for further blind testing.

Sincerely,

Sheldon Rubin

Sheldon Rubin
Senior Project Engineer
Vehicle Engineering Division

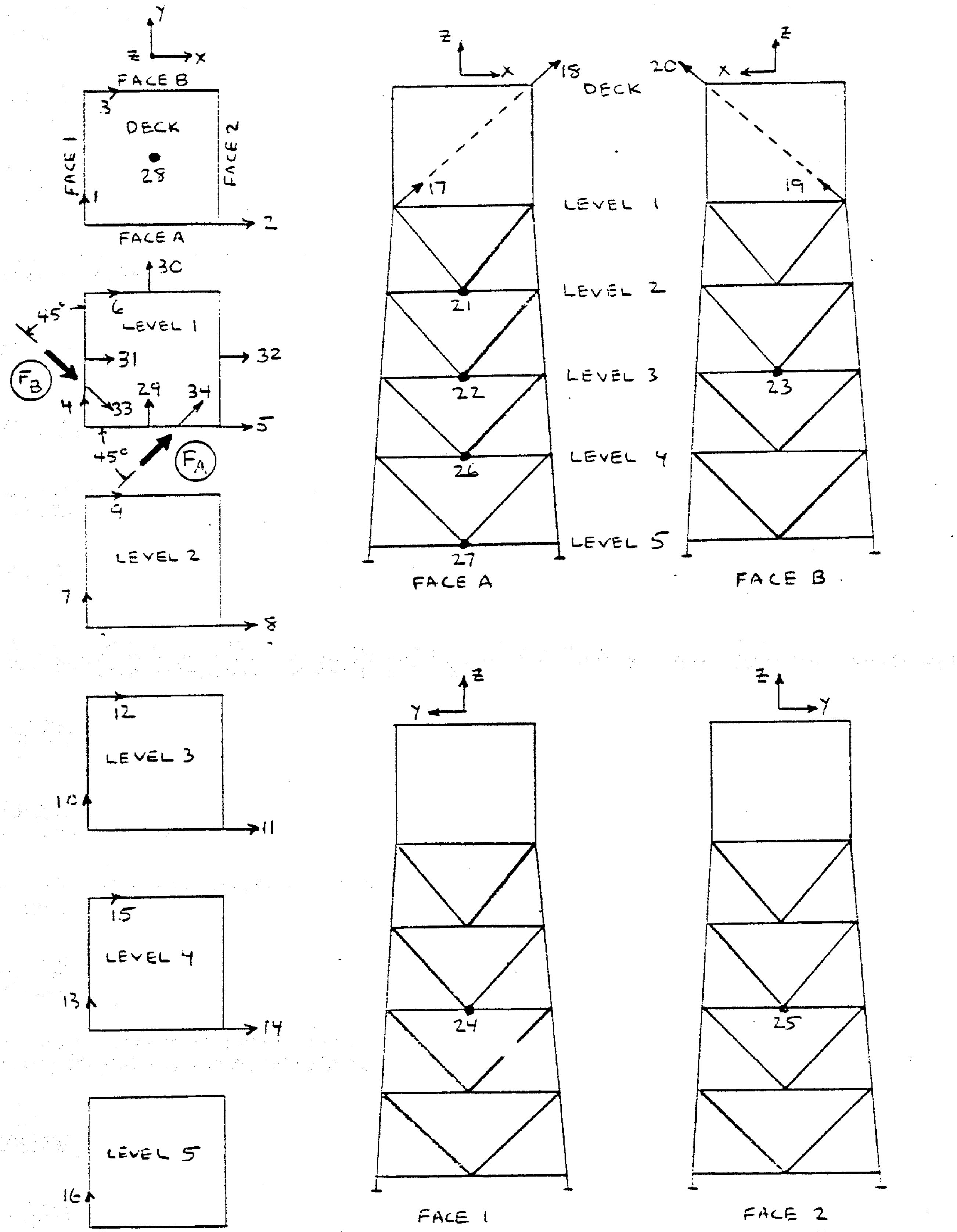
SR:mb

cc: J. B. Gregory
N. Perrone

ACCELEROMETER & FORCE POSITIONS

AEROSPACE BASELINE TESTS

15 SEP 80



Notes: F_A & F_B are at 1/3 position along member and in x,y plane

17-20 are diagonally directed as shown; 28 is z directed; others in x,y plane

Response Form for the
Round Robin NDE
of
Scale Model Tower Tests

Four tests have been conducted on a scale model of an off-shore tower structure.

Test data, as requested by each test advocate, has been sent under separate cover to each advocate.

To evaluate each technique it is requested that the following response be given to each of the four test scenarios after the baseline tests and not including the baseline tests.

1. Accuracy of Methods to Predict a Failure

The success or failure of your technique to predict a tower member failure (if one exists), or to predict that no failure has occurred (if none exists) should be recorded. The response expected is as follows:

For the test data series ___1___, Test Scenario No. ___1___, there was:

(a) No failure ____; Confidence level * ____%
(b) A failure ___X___; Confidence level * ___100___%
(c) Cannot predict ____

* Your prediction confidence level should be given as a percentage, assigning a value 0% to 100% (where 100% would indicate a completely confident prediction).

2. Locating the Failure

If possible, locate the failure in the tower.

For the test data series 1

Test Scenario No. 1, the:

(a) Tower level at which the failure occurred is: leg bottom ("foundation").

(b) The face on which the failure occurred is: (inapplicable).

(c) The location of the member is (x,y,z coordinates of member ends) leg A1 or B2 at bottom.

(d) No failure occurred. ☐

(e) Cannot locate a failure. ☐

3. Comments

a. From fundamental modes and abovewater accelerometers (1-6):

i. A1 or B2 leg bottom failure indicated by large reduction (~10%) in lateral mode through A1-B2 corners and virtually no change in other two modes.

ii. Above assessment further supported by large increase in net shear flexibility for jacket/foundation below level 1.

iii. We believe that identification of particular corner of failure (A1 or B2) would have been possible if data from abovewater upward angled accelerometers (17-20) or vertical accelerometer 28 had been properly provided. An apparent mixup in the data manipulations in the laboratory led to the unavailability of this data.

b. From fundamental modes with both abovewater and underwater leg accelerometers (1-15):

i. Observations support above assessment.

ii. Absence of diagonal failure(s) substantiated by lack of change in relative flexibility across individual bays.

iii. No further identification of failure available from underwater data.

Response Form for the
Round Robin NDE
of
Scale Model Tower Tests

Four tests have been conducted on a scale model of an off-shore tower structure.

Test data, as requested by each test advocate, has been sent under separate cover to each advocate.

To evaluate each technique it is requested that the following response be given to each of the four test scenarios after the baseline tests and not including the baseline tests.

1. Accuracy of Methods to Predict a Failure

The success or failure of your technique to predict a tower member failure (if one exists), or to predict that no failure has occurred (if none exists) should be recorded. The response expected is as follows:

For the test data series ___1___, Test Scenario No. ___2___, there was:

(a) No failure ____; Confidence level * ____%
(b) A failure ___X___; Confidence level * ___50___%
(c) Cannot predict ____

* Your prediction confidence level should be given as a percentage, assigning a value 0% to 100% (where 100% would indicate a completely confident prediction).

2. Locating the Failure

If possible, locate the failure in the tower.

For the test data series ____1____

Test Scenario No. ____2____, the:

(a) Tower level at which the failure occurred is: ____5____.

(b) The face on which the failure occurred is: ____unknown____.

(c) The location of the member is (x,y,z coordinates of member ends) ____unknown____

____.

(d) No failure occurred. ☐

(e) Cannot locate a failure. ☐

3. Comments

a. From the abovewater accelerometers (1-6, 29-32):

i. Observed are a very weak reduction in fundamental torsional mode frequency (0.1%), no change in the two fundamental laterals, and a 1% increase in the fundamental brace mode having predominant motion at level 5 ($\sim$ 41 Hz). According to our analytical studies, these observations are inconsistent with all major damage possibilities identified in paragraph 3.5.1 of the plan, except for horizontal failure most likely at level 5.

ii. Noticeable change in participation of modes within a group in the 40-45 Hz range, and the absence of such indication for higher modes primarily involving higher tower levels, also suggest the possibility of horizontal failure at level 5.

iii. Our net assessment is a possible horizontal failure at level 5, given with 50% confidence in view of the weakness of the observed changes. The possibility of cracking of horizontal and or diagonal members in one of the lowest K-braces, or even the absence of a failure, cannot be ruled out. There was no basis for identifying the face on which failure occurred.

b. From the abovewater and underwater leg acceleromters (1-15): Overall bay flexibility indications in the three fundamental modes show no significant changes from the baseline condition. Therefore <u>any damage present would not be significant in terms of overall strength of the tower</u> (for loadings producing responses predominantly in the fundamental tower modes).

Response Form for the

Round Robin NDE

of

Scale Model Tower Tests

Four tests have been conducted on a scale model of an off-shore tower structure.

Test data, as requested by each test advocate, has been sent under separate cover to each advocate.

To evaluate each technique it is requested that the following response be given to each of the four test scenarios after the baseline tests and not including the baseline tests.

1. Accuracy of Methods to Predict a Failure

The success or failure of your technique to predict a tower member failure (if one exists), or to predict that no failure has occurred (if none exists) should be recorded. The response expected is as follows:

For the test data series ___1___, Test Scenario No. ___3___, there was:

(a) No failure ____; Confidence level * ____%

(b) A failure __X__; Confidence level * __100__%

(c) Cannot predict ____

* Your prediction confidence level should be given as a percentage, assigning a value 0% to 100% (where 100% would indicate a completely confident prediction).

2. Locating the Failure

If possible, locate the failure in the tower.

For the test data series 1

Test Scenario No. 3, the:

(a) Tower level at which the failure occurred is: between levels 4 and 5 (lowest bay).

(b) The face on which the failure occurred is: B.

(c) The location of the member is (x,y,z coordinates of member ends) either one or both of the diagonals.

(d) No failure occurred. ☐

(e) Cannot locate a failure. ☐

3. Comments

a. From fundamental modes and abovewater accelerometers (1-6):

i. Frequency reductions in X and T (torsion) of 1.3% and 1.9%, respectively, and no reduction in Y, indicate brace severance(s) on either face A or face B.

ii. Severance(s) on face B indicated by its greater flexibility (with respect to face A) as revealed by mode shapes of X and T at level 1

iii. Diagonal failures(s) between level 1 and 2 (uppermost bay) not indicated due to smallness of frequency changes.

iv. Horizontal severance(s) below level 2 not indicated because theory predicts nearly undetectable frequency changes.

v. Greater reduction in T vs. X suggests not a level 2 horizontal failure.

vi. Net assessment is severance of one or both diagonals in single bay below level 2 on face B.

b. From fundamental modes with both abovewater and underwater leg accelerometers (1-15):

i. All above conclusions substantiated.

ii. Greatly increased flexibility in bay below level 4 (lowest bay) clearly reveals diagonal severance(s) in this bay.

iii. Net assessment is severance of one or both diagonals in lowest bay on face B.

Response Form for the
Round Robin NDE
of
Scale Model Tower Tests

Four tests have been conducted on a scale model of an off-shore tower structure.

Test data, as requested by each test advocate, has been sent under separate cover to each advocate.

To evaluate each technique it is requested that the following response be given to each of the four test scenarios after the baseline tests and not including the baseline tests.

1. <u>Accuracy of Methods to Predict a Failure</u>

The success or failure of your technique to predict <u>a tower member failure</u> (if one exists), or to predict that <u>no failure</u> has occurred (if none exists) should be recorded. The response expected is as follows:

For the test data series ___1___, Test Scenario No. ___4___, there was:

(a) No failure ___X___; Confidence level * ___100___ %
(b) A failure ______; Confidence level * ______ %
(c) Cannot predict ______

* Your prediction confidence level should be given as a percentage, assigning a value 0% to 100% (where 100% would indicate a completely confident prediction).

2. Locating the Failure

If possible, locate the failure in the tower.

For the test data series 1

Test Scenario No. 4, the:

(a) Tower level at which the failure occurred is: ______.

(b) The face on which the failure occurred is: ______.

(c) The location of the member is (x,y,z coordinates of member ends) ______.

______.

(d) No failure occurred. [X]

(e) Cannot locate a failure. [ ]

3. Comments

Data were identical to baseline data.

Abovewater corner lateral accelerometers would have been sufficient for a positive diagnosis of No Change.

APPENDIX C

DAMAGE SCENARIOS - MEGA ENGINEERING (11/16/81)

MEGA ENGINEERING
NOVEMBER 16, 1981

PRELIMINARY RESULTS OF THE ROUND ROBIN NDE TEST PROGRAM FOR OFFSHORE STRUCTURAL INTEGRITY

BASED UPON TESTS CONDUCTED AT NASA/GSFC,
GREENBELT, MARYLAND

FOR:

ONR STRUCTURAL MECHANICS PROGRAM
AND U. S. GEOLOGICAL SURVEY R & D PROGRAM

SECTION I
INTRODUCTION

1.1 Purpose of Tests

The Non-Destructive Evaluation (NDE) Round Robin test series provides an evaluation of non-destructive techniques for determining the integrity of offshore type structures. The test program also evaluates current NDE technology and documents this technology's capabilities for evaluating structural inspection and monitoring in a blind mode. The results of this evaluation program will provide the sponsors with test validation of techniques based initially upon scaled model test performance of each technique.

1.2 Techniques Being Evaluated

Presently the program has evaluated four NDE techniques including:

- Frequency Monitoring Method
- Internal Friction Monitoring Method
- Random Decrement Method
- Acoustic Emissions Method
- Ultrasonic Inspection Technique

Using a series of laboratory tests, various advocates of each method developed test and data reduction procedures within their independent laboratories.

Using a series of four (4) blind-mode tests conducted by an independent NASA test laboratory and coordinated by an independent test coordinator, each technique advocate was provided data for each different damage scenario. Each advocate had to reduce this test data which was provided to him in his prescribed format. The advocates then predicted whether or not damage had occurred, the damage location and type. The results of each advocate's evaluations will be ranked and the ability of each technique to predict the type and location of damage in a series of tests will be evaluated.

1.3 Description of Methods Evaluated

The RANDOMDEC technique is a general method of analysis being studied at The University of Maryland. In this method the time history of response at selected locations within the structure is monitored for changes in natural frequencies or damping. This technique analyzes the measured output of the structure at these points when the structure is subjected to some ambient random input. The technique's ability to obtain a unique response signature for different structural modes enables detection of early damage before overall structural integrity is affected.

Internal Friction Monitoring is a technique developed by Daedalean Associates, Inc. This technique measures the increase in internal damping during the service life of a structure. This increasing internal damping could indicate progressive fatigue from which remaining structural life can be determined. This technique was dropped from the test program after initial tests indicated the procedure could not be conducted in accordance with the guidelines set up for the test series.

The Frequency Response Monitoring technique relies on the identification of natural frequencies and mode shapes associated with a structure. This method is being evaluated by the Aerospace Corporation. This is accomplished using a finite element model and correlating data from this model with field test data representative of the actual structure. Parameters are selected which will serve as indicators of the structural integrity of the tower. Changes in these parameters could indicate degradation of the structure. The diagnosis requires that structural response data for selected locations from ambient random forcing functions be compared with similar responses from the finite element model response.

Acoustic Emission is a phenomena whereby transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material. Acoustic emission testing requires that an energy reservoir (i.e., strain energy) must be present. A propagating flaw in a structure then transduces minute amounts of strain energy to a transient elastic wave which propagates at the speed of sound in the structure. The spectral content of this signal is very broad and can be detected up to frequencies as high as 30 MHz. Most practical applications involve monitoring frequencies from 30 kHz to 1 MHz. The Federal Highway Administration was unable to complete its participation in the program.

2.6 ULTRASONIC INSPECTION TECHNIQUE

A dual element transducer technique for characterizing defects in offshore structural components was evaluated.

A global inspection procedure was used which allows ultrasonic waves to travel completely around a K-joint. A matched filter signal processing technique was developed and which looked for a change in the ultrasonic siognal that could be correlated with some kind of damage at a particular location in the K-joint.

Data collection was as follows. Information from different locations was acquired. Every signal was stored in a storage device for further signal processing.

The procedure for detecting changes in the vicinity of a K-joint was approached by a correlation analysis or by a matched filter technique. The underlying philosophy is basically template matching. This requires the generation of a library of signals obtained from a collection of K-joints.

1.4 Model Laboratory Tests Conducted

Initially a series of laboratory dynamic tests were conducted to provide the initial baseline data to each NDE method advocate. This baseline data provided each advocate with an understanding of the tower's physical performance prior to any damage and against which an advocate could compare later test data representive of different damage conditions on the tower.

All tests were conducted at the NASA Goddard Space Flight Center in Greenbelt, Maryland. Tests were developed, monitored and coordinated by Mega Engineering for the USGS and ONR sponsors.

1.5 Structures Used In the Validation Tests

Figures 1 and 2 below show two of the structures used in the validation test series for the NDE studies. The first structure is a 1:13.8 scaled model of a four legged off shore platform built by the University of Maryland. This model is a welded tubular steel structure with a honeycomb sandwich reinforced deck structure. During testing its four legs were rigidly mounted to the test facility floor. The second structure used in the validation test program was a 1/4 scaled model of a typical tower K joint . This joint was used only for verification of damage using acoustic emission techniques.

1.6 Damage Modes Used For Evaluation

A set of four blind mode test were conducted on the scaled model tower. The damage mechanisms had to be carefully selected so that it would not bias the test toward one advocate. The expectations of some advocates were that continual monitoring would be carried out during a "fatigue" type failure. However due to the nature of the tests and different requirements of each advocate this was not possible. Rather a discrete damage mode was applied to the tower. Each of the four tests were as follows:

Test-1 Remove the bolts and shim plate from one support leg leaving a gap under that leg. This would qualify as major damage corresponding to a foundation change.

Test-2 Partial saw cut thru horizontal members on face B at the level 4* at a section 1" fom vertical leg with two saw cuts (i.e. one at each end). This test was intended to simulate moderate damage. The vertical leg was re-bolted in place eliminating the first damage mode.

Test-3 Complete saw cuts thru the above members and also remove diagonal "V" members which tie into the horizontal member. This effectivly removed one bay of members from one face. The intent was to provide a major damage which would leave no "tell-tale" low frequencies indicative of unsupported or cantilevered members.

Test-4 Repeat the base line tests

1.7 Results of Advocates preditions.

Copies of each advocates response is attached. The following table provides a summary of their response in terms of predicting if damage has occurred.

Advocate Method	U of Maryland Random Dec.	Aerospace Corp. Frequency and Shear
Test 1	correct	correct
confidence	100%	100%
Test-2	correct	correct
confidence	100%	50%
Test 3	correct	correct
confidence	100%	100%
Test4	correct	correct
confidence	100%	100%

Aerospace Note:
*Cuts actually at level 5.

PROGRAM GOALS:

PRIMARY GOALS:

TO EVALUATE TECHNIQUES WHICH MERIT FURTHER DEVELOPMENT

SECONDARY GOALS:

(A) DISCRIMINATE BETWEEN FAILURE AND NON-FAILURE

(B) DISCRIMINATION OF THE DEGREE OF DAMAGE

(C) DISCRIMINATION OF LOCATION OF DAMAGE

TEST APPROACH

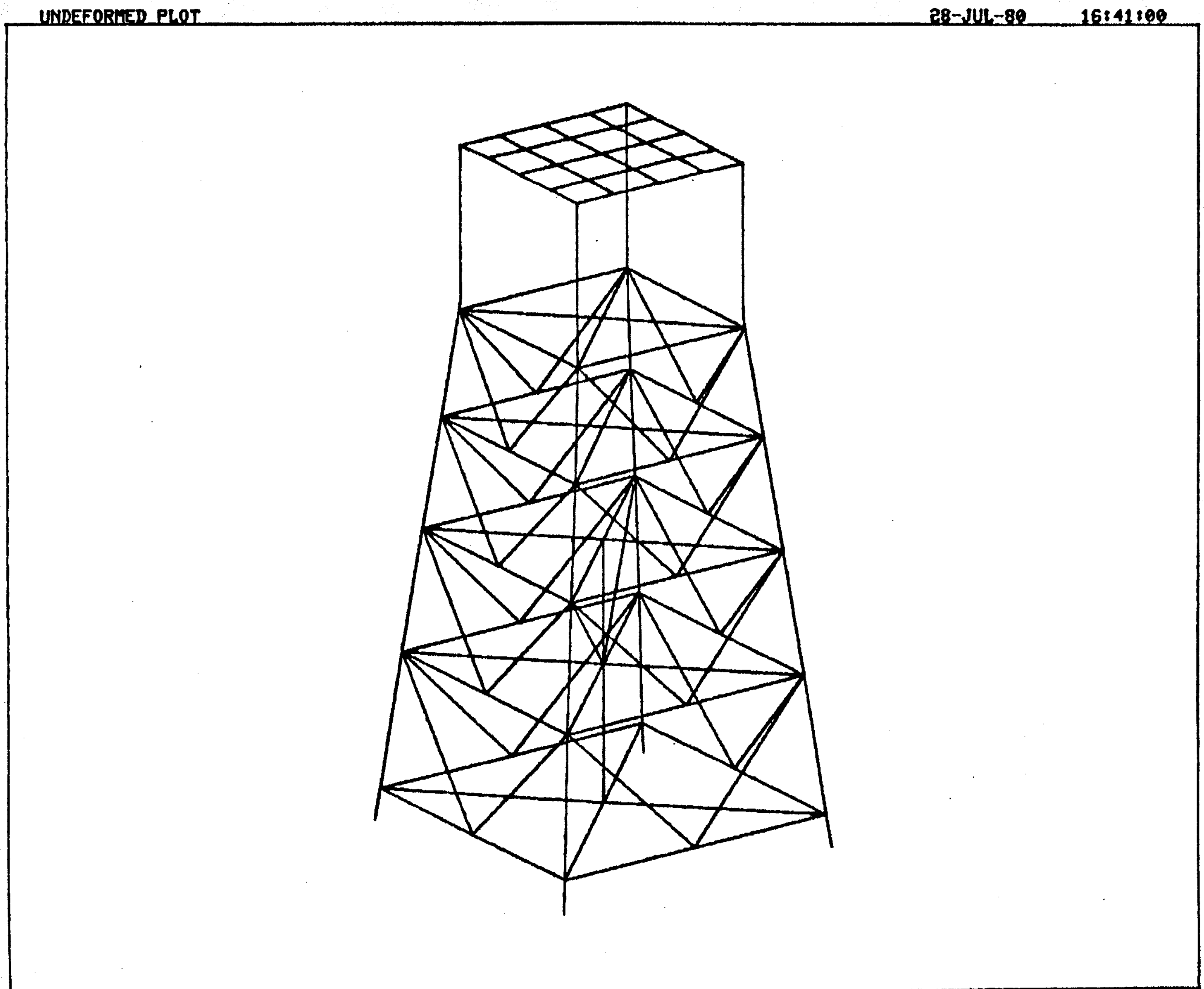
- o CONDUCT A SERIES OF TESTS ON SCALED MODELS OF OFF-SHORE TYPICAL STRUCTURES
  - 4 LEG PLATFORM
  - K JOINT

- o TEST IN A MEANINGFUL WAY REPRESENTATIVE OF OFF-SHORE PLATFORMS

- o TESTS TO BE CONDUCTED IN A BLIND MODE

- o <u>FAILURE MECHANISMS</u> PROPOSED:
  - SEVERED MEMBERS
  - JOINT CRACKING

- o NON-FAILURE CHANGES PROPOSED:
  - CHANGE IN DECK MASS
  - CHANGE IN BASE SUPPORT



NASTRAN Plot of Tower Model

ASSEMBLY OF TEST PLANS

- o ADVOCATES DEVELOPED INDIVIDUAL TEST PROCEDURES AND SENSOR LOCATIONS

- o ALL SENSORS WERE LOCATED ON MODELS AND TEST PROCEDURES WERE INTEGRATED INTO ONE PLAN

- o PROBLEMS

  - SENSOR LOCATIONS SEVERELY LIMITED TYPES OF DAMAGE ALLOWED

  - TIME AND SET UP COMPLEXITIES REQUIRED TESTING FOR EACH ADVOCATE SEPARATELY

  - DIFFICULTIES ENCOUNTERED WITH TEST DATA COLLECTION AND TRANSMITTAL

    - TAPE RECORDER

    - CHANNELS OF DATA MISSING

  - ORDER OF DAMAGE INFLICTION BECOMES IMPORTANT

POSSIBLE DAMAGE SCENARIOS

CONDITION	MAJOR DAMAGE
1	SEVERED DIAGONAL BRACE - ONE FACE
2	2 SEVERED DIAGONALS (ONE ON OPPOSITE FACES)
3	SEVERED HORIZONTAL AT BASE
4	2 SEVERED HORIZONTALS AT BASE (ON AN OPPOSITE FACE)
5	CHANGED FOUNDATION CONDITION
	MINOR DAMAGE
6	BENT DIAGONAL IN UPPER BAY
7	CHANGE IN DECK MASS
8	SIMULATED MARINE GROWTH
9	CRACK IN ONE OR TWO HORIZONTAL MEMBERS
10	PROGRESSIVE CRACKING OF HORIZONTAL AND DIAGONAL MEMBERS
11	INSTALLATION OF ONE OR TWO RISER PIPES

TEST SCENARIOS SELECTED

		Type of Damage
Test A	BASELINE - UNDAMAGED TOWER	NONE
Test 1	REMOVE BOLTS AND SHIM PLATES FROM ONE LEG ATTACHMENT TO DECK*	#5 - Major
Test 2	PARTIAL SAW CUT THROUGH 2 MEMBERS (LEVEL 4 - FORCE B) AT JOINT**	#9 - Minor
Test 3	REMOVAL OF HORIZONTAL AND "V" DIAGONALS ON SIDE B - LEVEL 4***	#1 - Major
Test 4	PLAYBACK OF BASELINE TEST RECORDINGS TO ADVOCATES	NONE

Aerospace Notes:

*. . . leg attachment to foundation (not to deck).

**Saw cuts through a horizontal at level 5.

***Removal of horizontal at level 5 and the two diagonals above it.